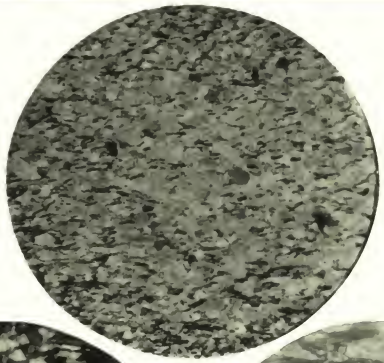

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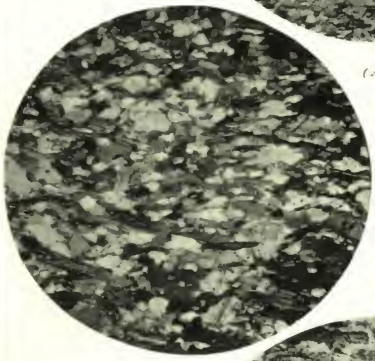

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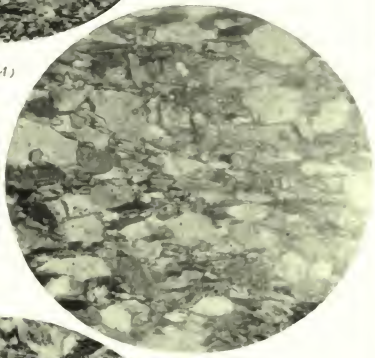

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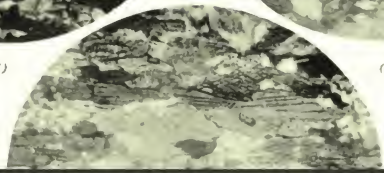

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The Mesabi iron-bearing district of Minnesota

Charles Kenneth Leith

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DEPARTMENT OF THE INTERIOR

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UNITED STATES GEOLOGICAL SURVEY

CHARLES D. WALCOTT, DIRECTOR

THE

MESABI IRON-BEARING DISTRICT OF MINNESOTA

BY

CHARLES KENNETH LEITH

CHARLES RICHARD VAN HISE, Geologist in Charge

WASHINGTON
GOVERNMENT PRINTING OFFICE
1903

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LETTER OF TRANSMITTAL.

DEPARTMENT OF THE INTERIOR,
UNITED STATES GEOLOGICAL SURVEY,
DIVISION OF PRE-CAMBRIAN AND METAMORPHIC GEOLOGY,
Madison, Wis., June 23, 1902.

SIR: I have the honor to transmit herewith the manuscript of a monograph on The Mesabi Iron-bearing District of Minnesota, by Charles Kenneth Leith. Discovered only about ten years ago, in the early nineties, the Mesabi district has to-day no rival in its production or reserve of iron ore. The geological succession in the district, the unusual size, shape, and structure of the ore bodies, their manner of development, and the peculiar and rapid methods of exploitation of the ore, all present features of unusual scientific and economic interest.

This monograph is one of a series planned to treat the six iron-bearing districts of the Lake Superior region. Monographs on the Penokee-Gogebic, Marquette, and Crystal Falls districts have been published, in the order named. This, on the Mesabi, is therefore the fourth. The last two of the series treat of the Vermilion and Menominee districts. The former, by J. Morgan Clements, is ready for the printer, and the latter, by W. S. Bayley, is nearing completion.

The execution of the full plan of the old Lake Superior Division of the United States Geological Survey will be marked by the publication of a closing monograph entitled The Geology of the Lake Superior Region, which will contain a general discussion of the geology of that region, including a summary treatment of each of the iron-bearing districts, and a general discussion of the ore deposits. This monograph is in preparation.

Very respectfully, your obedient servant,

C. R. VAN HISE,
Geologist in Charge.

HON. CHARLES D. WALCOTT,
Director of United States Geological Survey.

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OUTLINE OF MONOGRAPH.

Chapter I contains a general account of the geography, topography, and geology of the Mesabi district. The district lies northwest of Lake Superior and extends from near Grand Rapids, on the Mississippi River, a little north of east to Birch Lake, a distance of approximately 100 miles. Its width varies from 2 to 10 miles, and the total area is about 400 square miles. The main topographic feature is a ridge, known as the Giants (or Mesabi) range, which extends the length of the district. The geologic formations represented in the district belong, in ascending succession, to the Archean, Lower Huronian, Upper Huronian, Keweenawan, Cretaceous, and Pleistocene. They are all separated by unconformities. The core of the Giants range is formed by Archean and Lower Huronian rocks, except for the portion in ranges 12 and 13, where Keweenawan granite forms the core. On the south flank rest the Upper Huronian rocks, containing the iron-bearing formation, with gentle southerly dips. The Keweenawan gabbro lies diagonally across the east end of the district. The Cretaceous rocks are found in small isolated patches in the western portion of the district. Pleistocene drift forms a more or less heavy mantle over all the underlying rocks.

In Chapter II is given the history of early explorations, discovery of ore, and the marvelous economic development of the district, together with summaries of literature on the geology of the area.

Chapter III treats of the Archean rocks. They consist principally of green rocks of great variety, including dolerites, metadolerites, basalts, metabasalts, diorites, and hornblendic, micaceous, and chloritic schists. The more massive rocks frequently have an ellipsoidal structure which is characteristic of the green igneous rocks of other parts of the Lake Superior region. In addition to the green basic rocks there are present small areas of granite and porphyritic rhyolite.

In Chapter IV the Lower Huronian series is described. The series consists of sediments and granite. The sediments are graywackes, slates, and conglomerates, all metamorphosed, with bedding and schistosity practically vertical. They may be as thick as 10,000 feet, but it is thought more probable that the thickness does not exceed 5,000 feet. The Lower Huronian sediments rest unconformably upon the Archean rocks, as shown by basal conglomerates containing fragments of all the varieties of rocks found in the Archean. Previous to the work done in connection with the preparation of this monograph, the presence of the Lower Huronian

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series of sediments had not been determined, but everything beneath the Upper Huronian or Animikie had been mapped as Keewatin or Archean. The Lower Huronian granite forms the main mass of the Giants range westward from a point near the east line of R. 14 W. It is intrusive into both the Archean rocks and the Lower Huronian sediments and has produced strong exomorphic effects in both.

Chapter V contains an account of the Upper Huronian series, of importance because it includes the iron-bearing formation. The series consists of three formations—the Pokegama quartzite at the base, above this the Biwabik formation (iron-bearing), and above this the Virginia slate.

The Pokegama quartzite (Section I) comprises vitreous quartzite, micaceous quartz-slate, and conglomerate. The thickness ranges from 0 to 500 feet, averaging about 200 feet. The conglomerate at the base indicates unconformable relations of the Pokegama formation to the Archean and Lower Huronian rocks.

The Biwabik formation (Section II), the iron-bearing formation, comprises ferruginous, amphibolitic, sideritic, and calcareous cherts, siliceous, ferruginous, and amphibolitic slates, paint rocks, "greenalite" rocks, sideritic and calcareous rocks, conglomerates and quartzites, and iron ores. All but the last are described in this chapter. The iron ores are reserved for description in Chapter VIII. Cherts make up the bulk of the formation. The original rock of the formation is shown to consist largely of minute granules of green ferrous silicate, thus confirming Spurr's conclusion. The material was called glauconite by Spurr, but is here determined to be a hydrous ferrous silicate entirely lacking potash, and thus not glauconite. It is named "greenalite" for convenience in discussion. The cherts and iron ores are shown to develop mainly from the alteration of the greenalite granules. The slates are in thin layers interbedded with the other phases of the iron formation. The paint rocks result from the alteration of the slates. The conglomerates and quartzites form a thin layer from a few inches to perhaps 15 feet or more in thickness at the base of the formation. They pass upward into ferruginous cherts of the iron formation rather abruptly, though usually at the contact the chert and quartzite are interleaved for a few feet. The conglomerate of the iron formation rests upon Pokegama quartzite, indicating a slight erosion interval between the Biwabik and Pokegama formations, although the interval is not shown by discordance in bedding, which is parallel in both. Heretofore the quartzite and conglomerate in the iron formation have not been discriminated from the rocks of the Pokegama formation. In the eastern portion of the range the iron formation is in contact with the Keweenawan gabbro and granite, and near this contact has suffered profound metamorphism. The characteristic rocks of this area are amphibole-magnetitecherts. The thickness of the formation may vary from 200 to 2,000 feet. The average may be 1,000 feet.

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The Virginia slate (Section III) is essentially a soft slate or shale formation, but it contains graywacke phases, near its base a little limestone, and near its contact with the gabbro is metamorphosed into a cordierite-hornfels. The normal slate phases of the formation may be distinguished with difficulty in isolated occurrences from the slate layers in the Biwabik formation. The separation of the two is of importance to the explorer, and hence an attempt is made to determine criteria for their discrimination. The thickness of the Virginia formation can not be measured within the district, but from analogy with the Penokee-Gogebic district and the extent of the low, flat-lying area south of the Mesabi range supposed to be occupied by the slate, the formation is believed to have a very considerable thickness. The slate grades, both vertically and laterally, into the Biwabik formation.

The structure of the Upper Huronian series is described in Section IV. The entire series is well bedded, conformable in structure (although having a thin conglomerate between the Biwabik and Pokegama formations), and dips in southerly directions at angles varying from 5 to 20 degrees and exceptionally at higher or lower angles. The series is gently cross folded and the axes of the cross folds pitch in southerly directions. Accompanying the folding is considerable jointing, especially in the brittle Pokegama and Biwabik formations. Indeed, in these two formations the folding is brought about mainly through relatively minute displacements along joints, while in the Virginia formation the folding has taken place mainly by the actual bending of the strata.

The thickness of the Upper Huronian series (Section V) within the limits of the district mapped may average about 1,500 feet; but if the total thickness of the slate formation outside the limits of the district be taken into account, the total thickness of the Upper Huronian series is probably several times this figure.

The relations of the Upper Huronian series (Section VI) to the subjacent formations are those of unconformity, as evidenced by basal conglomerates, discordance in dip, difference in amount of deformation and metamorphism, distribution of the series, and relations to intrusives.

In Chapter VI the Keweenawan, Cretaceous, and Pleistocene rocks are described.

The Keweenawan rocks (Section I) consist of gabbro, diabase, and granite, all of which are intrusive into the rocks with which they come into contact. The north edge of the gabbro runs diagonally across the east end of the district from southwest to northeast, resting upon the edges of each of the members of the Upper Huronian series, and at Birch Lake against the Lower Huronian granite. North of the gabbro margin in range 12 are isolated exposures of diabase which may represent sills associated with gabbro intrusion. The granite forms the crest of the Giants range through ranges 12 and 13. This granite has not heretofore

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been discriminated from the Lower Huronian granite. The exomorphic effect of the gabbro and the granite upon the Upper Huronian series has been profound.

Cretaceous rocks (Section II) are found in a few isolated remnants in the western portion of the range. They consist of conglomerate and shale, and contain fossils showing them to belong to the Upper Cretaceous—not older than the Benton and probably not younger than the Pierre horizon.

The Pleistocene deposits (Section III) form a heavy covering over the district. On the upper slopes of the range many rock exposures project through, but on the lower slopes the rock series are commonly buried to depths ranging from 20 to 150 feet. The glacial deposits consist of stratified and unstratified drift, belonging principally to the Itasca and Mesabi moraines of the latest ice incursion. The movement of the ice was mainly from northeast to southwest, as shown by glacial striæ. Several remarkable, steep-walled gorges through the crest of the Giants range at high elevations are believed to be the work of glacial streams escaping from a great lake ponded between the Giants range and the ice front when the glacier had drawn back north of this area.

Chapter VII contains a résumé of the geologic development and a correlation of the formations. The résumé of geologic development is itself a summary and will not be here repeated. The essential feature of the correlation is the equivalence of the Archean, Lower Huronian, Upper Huronian, and Keweenawan series with similar series in other parts of the Lake Superior country. Prior to the work in the Mesabi district done in connection with the preparation of this monograph, everything below the Upper Huronian (or Animikie) had been mapped as Archean or Keewatin. The work of the Survey has shown the supposed Archean or Keewatin series to consist of two series, an igneous one below and a sedimentary one above, separated by a profound unconformity, to be correlated respectively with the Archean and Lower Huronian series of other parts of the Lake Superior region. The remarkable similarity of the Upper Huronian series to that of the Penokee-Gogebic district is again emphasized and the probability of their areal connection is discussed.

Chapter VIII is a description of the iron-ore deposits. The features treated are distribution, shape, size, kinds, minerals and rocks contained in the ore, chemistry, texture and structure, rocks forming the bottoms and sides, structural relations of the ores to the adjacent rocks, petrographic relations of the ores to the adjacent rocks, and drainage. The ores are in basin-shaped deposits, with great variety and irregularity of shape, but the horizontal dimensions are usually great as compared with the vertical dimensions. At the edges the layers of ore grade directly into the layers of wall rock, principally ferruginous chert. The deposits lie, for the most part, near the axes of gentle troughs formed by the folding of the iron-formation strata, but in

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many cases the strata in the ore and adjacent rocks have essentially monoclinal dips, indicating the deposit to be independent of a synclinal structure in the iron-formation layers.

Chapter IX contains a discussion of the origin of the ores. The ores are shown to develop mainly from the alteration, under surface conditions, of green ferrous silicate granules, as first pointed out by Spurr. The green granules, however, instead of being glauconite, as maintained by Spurr, are believed, from their lack of potash, to be of different nature, and have been given the name greenalite. Their development is believed to be analogous to that of the iron carbonates of other parts of the Lake Superior region. That is, the iron was carried to the Upper Huronian ocean in solution, probably as carbonate, was precipitated as ferric hydrate, was buried with the vegetable material and reduced to the protoxide form, and was then combined with silica to form ferrous silicate. In the Gogebic district, where silica was not present in so great abundance, the protoxide combined for the most part with carbon dioxide to form iron carbonate. The shapes of the granules may be due to replacement of minute shells, such as those depositing glauconite or those giving shape to the granules of much of the Clinton ore.

The secondary concentration of ore into deposits has resulted from the surface alteration of the ferrous silicate (greenalite), under essentially surface conditions, since the iron formation was first exposed to weathering. The process has consisted essentially in the decomposition of the ferrous silicate, the oxidation of the protoxide of iron to hematite or ferric hydrate, and the segregation of the iron and silica. Where this has occurred on a small scale, banded ferruginous cherts have resulted; where on a large scale, the iron-ore deposits have been formed. During the change both iron and silica have been carried in solution. At the present time waters flowing through the altered portions of the formation are concentrating ore by the solution and abstraction of silica, but little iron being carried in solution, as shown by analysis.

The localization of the ores by circulation of underground waters is described in detail. The ores are shown to develop both above and below ground water, to have been concentrated on impervious basements consisting of slaty layers in the iron formation, which have limited the circulation below, and to have been in part confined to troughs formed by the folding of such impervious strata and in part independent of them. They have, in short, developed in the irregular and ramifying channels of water circulation in gently dipping, much jointed strata. Finally, the apparent lack of ore deposits in the iron formation far under the edge of the Virginia slate is shown to be due to sluggish circulation under the slate because of the ponding of water under that impervious formation.

In the eastern portion of the range the iron oxide is mainly magnetite, associated with amphibolitic chert, and has not yet been found in large enough deposits to

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warrant mining. The explanation of the nature of the oxide and of the absence of ore deposits in this portion of the district is found in the presence of the Keweenawan intrusives. Prior to the Keweenawan intrusions the iron formation in the eastern end of the district had been exposed to erosion by the removal of the overlying Virginia slate. In the central and western portions the slate had not been removed. When the Keweenawan rocks were intruded the iron-formation rocks of the eastern end of the district were brought under deep-seated conditions, during which the changes in the original greenalite rock were those of partial oxidation and silicification, resulting in the production of amphibole-magnetite rocks. These rocks are stable and have not been considerably altered since their exposure to surface alterations by the erosion of the Keweenawan rocks. The rocks of the iron formation in the central and western portion of the district were not exposed to weathering agencies until after Keweenawan time, when the Virginia slate had been removed by erosion, and thus were never metamorphosed by the gabbro. Their alteration has been throughout under surface conditions, where abundance of oxygen and carbon dioxide makes possible the complete oxidation of the iron and the removal of silica on a large enough scale to cause the concentration of the ore bodies.

During the development of the iron-ore deposits erosion has continuously cut down the iron formation, and, because of the gentle dip of the strata, this truncation has been accompanied by the downward and lateral migration of the ore deposits. The deposits in their present position may be supposed to represent simply a stage in the process of concentration and migration. Glacial erosion has also cut down the ore deposits to a considerable extent.

The phosphorus in the ores is shown to be a concentration and not a residual product. The original greenalite rocks contain little or no phosphorus, while their altered equivalents, the ores and cherts, uniformly show small contents of phosphorus. The unaltered iron-formation slates also contain a lower percentage of phosphorus than their altered equivalents, the paint rocks.

The points of similarity and difference between the Mesabi ores and those of other Lake Superior ranges are briefly summarized.

Previous explanations of the origin of the ore are outlined and their relations to the present explanation shown.

Chapter X is devoted to economic features of interest, such as mining, transportation, production, reserve, ownership, prices, etc. The open-pit steam-shovel method of mining, characteristic of the district, is illustrated.

In Chapter XI exploration for ore is discussed and an attempt is made to give the criteria for locating explorations which the geologic structure and manner of development of the ore would seem to warrant.

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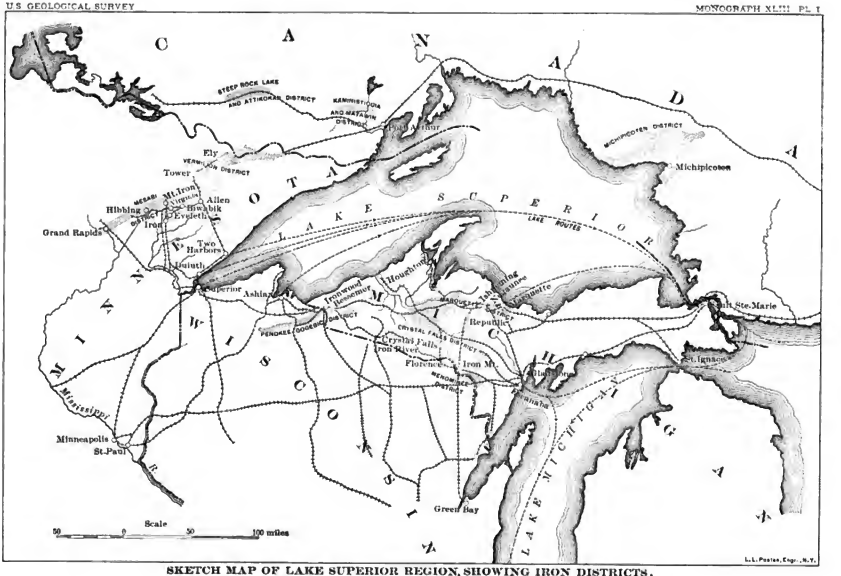

SKETCH MAP OF LAKE SUPERIOR REGION, SHOWING IRON DISTRICTS, SHIPPING PORTS, AND TRANSPORTATION LINES

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THE MESABI IRON-BEARING DISTRICT, MINNESOTA.

By Charles Kenneth Leith.

CHAPTER I.

INTRODUCTION.

The following monograph tells of the geologic and economic features and of the sudden and gigantic development of the Mesabi iron-bearing district of Minnesota, the sixth, last, and greatest of the iron ranges to be discovered in the United States portion of the Lake Superior region.

The writer's work upon the district has been done under the supervision and advice of Prof. C. R. Van Hise, geologist in charge. To him is due in large measure any credit this report may deserve. Indeed, the work has been largely the application in this district of principles and methods of work developed by him.

Field work in the Mesabi district was begun in the spring of 1900 and continued during the summers of 1900 and 1901. In the year 1901 M. H. Newman served as field assistant. Near the close of the field season of 1900 Professor Van Hise spent some time in the district. Immediately thereafter he and the writer prepared a brief preliminary report on the district, accompanied by a geologic map of the central portion, which was published in the Twenty-first Annual Report of the United States Geological Survey, as a part of a general paper on Lake Superior iron-ore deposits, by Professor Van Hise. At the close of the field season of 1901 the preparation of the final report and maps presented herewith was taken up.

The topography of the Mesabi district shown on the accompanying maps was sketched during the summers of 1899 and 1900 by a party of the United States Geological Survey consisting of E. C. Bebb, D. L. Fairchild,

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Louis B. Weed, and assistants, in charge of Mr. Bebb. Much information concerning section, town, and range lines and the subdivisions of sections has subsequently been furnished by Mr. D. L. Fairchild, who has had charge of parties engaged in locating the boundaries of properties of the Minnesota Iron Company. This information has applied particularly to the area between Eveleth and Mesaba station.

Since the work was begun in the Mesabi district the Survey has had access to an elaborate set of maps of the iron-bearing series, containing records of practically all of the exploration work done on the range, prepared by J. U. Sebenius, under the direction of W. J. Olcott, for the Lake Superior Consolidated Iron Mines, now a part of the United States Steel Corporation. These have been kept up to date by Mr. Sebenius for the United States Steel Corporation. Exploration of the iron formation in the Mesabi district is done largely by test pitting and drilling through the glacial drift which deeply covers the district, and if the records of test pits and drill holes are not collected and systematized at the time of the exploration the information is largely lost for purposes of mapping. It is apparent, therefore, that accurate mapping of the iron formation would have been quite impossible without access to such maps as those referred to.

Many other mining men and explorers, indeed practically all interested in the Mesabi district, have given the Survey information concerning their properties and have placed facilities for study at its disposal. The writer finds himself quite unable to present an adequate list of names or to make a satisfactory selection of a few names for special mention.

The mine photographs reproduced were furnished by W. J. Olcott, E. E. Sperry, George Dormer, E. R. Buckley, and local professional photographers.

To all whose cooperation has aided in the preparation of this report the Survey tenders thanks.

GEOGRAPHY AND TOPOGRAPHY.

The Mesabi iron district lies in the part of Minnesota which is northwest of Lake Superior. In shape and trend it is similar to the other iron districts of the Lake Superior region (see Pl. I). It extends from Grand Rapids, on the Mississippi River, in a direction ENE. to Birch Lake, a distance of approximately 100 miles, with a width varying from 2

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to 10 miles. Its area is about 400 square miles. Eastward from Birch Lake to Gunflint Lake and beyond are small patches of iron-formation material, and these areas have often been included in the Mesabi district, particularly by the early explorers.

The main topographic feature of the district is a ridge or "range" parallel to the longer direction of the district, known as the "Giants" or "Mesabi" range. Mesabi[a] (spelled also Mesaba and Missabe) is the Chippewa Indian name for "giant." In the west end of the district the Mesabi range merges insensibly into the level of the surrounding country, about 1,400 feet above sea level, or 800 feet above Lake Superior. Toward the east the elevation, with reference both to Lake Superior and to the surrounding country, increases; from range 18 to range 12 elevations of 1,800 and 1,900 feet above sea level, or 400 and 500 feet above the level of the surrounding country, are reached. For many miles both north and south of the range there is a comparatively low, flat area, and the Giants range, particularly its eastern portion, is a very conspicuous feature in the landscape.

While the general trend of the range is ENE., there are many gentle bends in the crest line, and in range 17 a spur, known locally as the "Horn," projects in a southwesterly direction for 6 miles. The crest of the range is in places broad and flat, in others comparatively narrow and sharp. The southern slope is very gentle; the northern slope is somewhat less so. At frequent intervals both crest and slopes are notched by drainage channels.

The Mesabi range, for the most part, forms a drainage divide, although it is crossed by drainage channels at several places. The drainage of the district is apportioned among three of the great river systems of the country—the Mississippi, St. Lawrence, and Nelson. In the western portion of the district, from Grand Rapids to within 3 miles of Hibbing, the southern slope is drained by the Mississippi River and its tributaries, the Prairie and the Swan. The Mississippi and the Swan cross the range. From 3 miles west of Hibbing to east of Iron Lake, near the east line of range 13, the district is drained to the south by the St. Louis River and its tributaries, the Swan, Embarrass, and Partridge. The Embarrass River

[a] The United States Board on Geographic Names has adopted this spelling. The term was originally applied to the elevation made by the gabbro eastward from Allen Junction to Gunflint Lake and beyond, but has since been applied as above.

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crosses the range. The St. Louis empties into Lake Superior, and thence the waters of the system are contributed to the St. Lawrence. From the east line of range 13 to east of Birch Lake the district is drained by the Dunka River, which crosses the range and is tributary northward to a lake system which discharges through Nelson River into Hudson Bay.

The northern slope of the Mesabi range is drained in part by the Mississippi, Prairie, and Embarrass rivers, flowing south, but aside from these the drainage of the north slope all goes northward into the lake system tributary to Hudson Bay. One of the feeders of this system, the Pike River, reaches well down into the southward-projecting spur of the range between the towns of Eveleth, Virginia, and McKinley, thus overlapping the headwaters of the Embarrass.

To anyone familiar with the Lake Superior region it is sufficient to say that the timber and soil of the Mesabi district are characteristic of the region. The forest includes the white pine, the yellow or Norway pine, tamarack, spruce, cedar, and balsam or balsam fir (jack pine). Scattered among them are hardwood trees, mainly poplar, birch, and maple. For the most of the district the forest is essentially coniferous, but over small areas the hardwood trees predominate. Tamarack, cedar, and spruce swamps occupy considerable areas, particularly along the lower slopes of the range. The exceedingly thick underbrush consists largely of hazel, maple, alder, ash, willow, cherry, and ground hemlock. Most of the pine has been cut.

Old choppings, windfalls, fires, underbrush, and swamps have combined to make the scene a desolate one for much of the district, and to make the traveling away from trails or roads most arduous. In the limited portions of the district where the original pines still stand, all the beauties of the Northern pine forest at its best are to be observed.

The district is heavily covered with glacial drift, consisting of sand, clay, and bowlders, the latter in some places so very numerous as to discourage attempts to clear the land for agricultural purposes. Up to the present time practically no land has been cleared outside of town sites and mining locations. There are, however, considerable areas in which the soil would yield abundantly on cultivation.

Along the Mesabi range are a number of mining towns, most of them marking mining centers; one only, Grand Rapids, on the west end of the

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range, owes its existence to lumber interests, and even this town is benefited by the exploration for ore in the western portion of the range. The towns are largely confined to the central portion of the district. Beginning at the Stevenson mine, in R. 21 W., there are towns at frequent intervals to Mesaba station, in range 14, and these intervals are likely to be further subdivided as the exploitation of the range proceeds. From Mesaba station to the east end of the range, and from the new town of Nashwauk to Grand Rapids, near the west end of the range, a distance in each case of a little over 20 miles, there are no settlements.

Three railways, all with terminals on Lake Superior, touch the range. The Duluth and Iron Range Railway crosses the district in R. 14 W., and sends out a branch to Biwabik, Stephenson, McKinley, Sparta, Eveleth, and Virginia. The Duluth, Missabe and Northern Railway approaches the range from the south through R. 18 W., and just before reaching the range sends out branches to Biwabik, Eveleth, Sparta, Virginia, Mountain Iron, and Hibbing. The Eastern Railway of Minnesota (the Great Northern) has three approaches to the range, one through R. 18 W., another through Hibbing, and a third through Grand Rapids. Branches connect with Stevenson, Chisholm, Buhl, Mountain Iron, and Virginia. The only large parts of the range not immediately accessible by railway are those between the Hawkins mine and Grand Rapids, and between Mesaba station and Birch Lake.

GENERAL GEOLOGY.

The succession of formations in the Mesabi district appears in the following table:

Succession of formations in Mesabi district.

Pleistocene.	
(Unconformity.)	
Cretaceous.	
(Unconformity.)	
Keweenawan	Great basal gabbro and granite, intrusive in all lower formations.
(Unconformity.)	
Upper Huronian (Mesabi series)	Virginia slate (upper slate formation).
(Unconformity.)	Biwabik formation (iron-bearing formation).
	Pokegama formation (quartzite and quartz-slate formation).
Lower Huronian	Granite, intrusive in lower formations.
(Unconformity.)	Slate-graywacke-conglomerate formation (equivalent to the Ogishke and Knife Lake formations of the Vermilion district).
Basement complex, or Archean	Greenstones, including basalts, diorites, diabases, etc., hornblende-schists, and porphyritic granites and rhyolites.

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The core of the Giants range is made up principally of granite of Lower Huronian and Keweenawan age, and subordinately of Archean igneous rocks. To the south of the igneous core, for a part of the district, are Lower Huronian sedimentary rocks, with bedding approximately vertical. Against the southern boundary of the Lower Huronian, or where the Lower Huronian is lacking, against the igneous core, lie the Upper Huronian sedimentary rocks. They dip gently to the south and underlie the greater portion of the southerly slopes of the range. On the southeast the Huronian rocks are limited by the Keweenawan gabbro, the north edge of which cuts across the Huronian formations diagonally from southwest to northeast. The Archean, Lower Huronian, and Upper Huronian series are separated from one another by unconformities. Glacial drift covers the district so thickly that rock exposures are rare on the lower slopes of the range, and only fairly numerous near the crest.

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CHAPTER II.

BRIEF HISTORY OF THE DISTRICT AND SUMMARY OF LITERATURE CONCERNING IT.

HISTORY AND LITERATURE OF THE DISTRICT PRIOR TO ITS OPENING.

In penetrating the vast wilderness north and west of the Great Lakes country, the early explorers were compelled for the most part to stick close to the waterways, for the nature of the country made travel for long distances exceedingly arduous by any other method than canoeing. Three of the canoe routes to the country northwest of Lake Superior cross the Mesabi range and its eastward continuation The Mississippi River and its tributaries, the Prairie and the Swan, touch the western portion of the district. Embarrass Lake, tributary to the St. Louis River and thence to Lake Superior and the St. Lawrence, crosses the Mesabi range near its east-central portion. Gunflint Lake, one of a chain of lakes tributary to Rainy River and Nelson River and thence to Hudson Bay, lies far to the east, on a continuation of what is now known as the Mesabi range. Thus it is that the first references to the Mesabi district found in literature concern the parts of the district immediately adjacent to these canoe routes. Brief descriptions of Pokegama Falls on the Mississippi River and adjacent areas were made by Maj. Z. M. Pike in 1810, by Lieut. James Allen and Henry R. Schoolcraft in 1832, and by J. N. Nicollet in 1841. In 1841 also Nicollet published his map of the hydrographic basin of the Upper Mississippi, on which the Mesabi range, called "Missabay Heights," was for the first time delineated, by hachures, although very imperfectly. In 1852 J. G. Norwood reported the occurrence of iron-formation material at Gunflint Lake and mentioned granite and gneiss seen in crossing the range at Embarrass Lake. In 1866 Col. Charles Whittlesey reported on explorations made in northern Minnesota during the years 1848, 1859, and 1864. He mentioned Pokegama Falls and made vague reference to the granitic rocks of the range. "Mesabi range" was used in an indefinite way

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to cover what are now known as the Mesabi and Vermilion ranges. In 1866, also, Henry H. Eames, the first State geologist of Minnesota, reported granite and gneiss seen on a trip across the range at Embarrass Lake. In describing the ranges of the northern part of the State, including the "Missabi Wasju," he stated that they appear to be traversed by metal-bearing veins. Presumably, however, this statement refers mainly to the Vermilion range. In a second report, published the same year, Mr. Eames is more explicit, and, referring to the general elevated area of the northern part of the State, including the Mesabi range, states: "In this region are found also immense bodies of the ores of iron, both magnetic and hematitic, occurring in dikes and associated with the rock in which it is found; in some of these formations iron enters so largely into its composition as to affect the magnetic needle." Pokegama Falls and Prairie River Falls were visited, and at the latter place the presence of "iron ore" was noted. These reports of Eames contain the first references to iron ore in the Mesabi district proper, although iron formation had been noted by Norwood in 1852 at Gunflint Lake.

From this time on desultory exploration work was done in certain portions of the district. It was confined for the most part to the area west of Birch Lake, in Rs. 12, 13, and 14 W., and to the vicinity of the Prairie River. No published accounts of the earlier portion of this exploratory work are to be found.

The first examination of the Mesabi range by a mining expert with particular reference to the occurrence of iron ore in workable deposits, noted in print, was made in 1875 by Prof. A. H. Chester, of Hamilton College, New York. Striking the Mesabi range at Embarrass Lake, he worked eastward toward Birch Lake. In his report (published in 1884) he called attention to the magnetic character of the iron in this area, and to the fact that the alternating iron layers are not thick or continuous. The percentage 44.68 was given as a fair average of iron in the rocks of this part of the district. In general, one gathers the impression that he was not favorably impressed with the economic prospects of this area. Between the time of Professor Chester's examination of the range, in 1875, and the publication of his report, in 1884, Prof. N. H. Winchell, State geologist of Minnesota, briefly noticed the Mesabi range in two of his reports. In 1879 he told of the occurrence of iron ore in R. 14 W., and published analyses. In 1881 he told of a trip from

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Embarrass Lake east to range 14, and noted the magnetic character of the iron formation in range 14, as well as its similarity to the formation at Gunflint Lake. Indeed, the iron formation in range 14 is called the "Gunflint beds." In 1883 Irving called the Mesabi iron-bearing rocks series "Animikie," a term which had been applied to similar rocks at Thunder Bay and westward to Gunflint Lake, and correlated the Animikie rocks with the "Original Huronian" rocks of the north shore of Lake Huron and with the iron-bearing series of the Penokee-Gogebic iron range of Michigan and Wisconsin. From this time on the term "Animikie" is much used in the literature on the Mesabi range to designate the iron-bearing series. In 1884, in the same report in which Chester's report was published, N. H. Winchell discussed the age of the Mesabi series of rocks, assigning them to the "Taconic," or Lower Cambrian, and, following Irving, correlated them with the iron-bearing rocks of the Penokee-Gogebic district. In the late eighties a number of other reports on the district were issued by the Minnesota survey, but they contain no important points not noted in reports above cited. This brings us to the opening of the district for mining.

OPENING AND DEVELOPMENT OF THE DISTRICT.

Since the late sixties there had been more or less exploration, particularly along the eastern portion of the district, from Embarrass Lake to Birch Lake, and the presence of iron-formation material had been recognized and discussed in the reports above mentioned. However, not a single deposit of iron ore of such size and character as to warrant mining had been shown up. In fact, the range had been "turned down" by many mining men who had examined it. This was largely because of the fact that they confined their attention principally to the eastern, magnetic end of the range, where exposures of the iron formation are numerous. Even up to the present time no ore has been found there in quantity. Yet the impression was gradually developing that iron ore in large quantity was to be found in this district, and a few prospectors were working diligently.

Among the more persistent of the Mesabi range explorers were the Merritts—Lon Merritt, Alfred Merritt, L. J. Merritt, C. C. Merritt, T. B. Merritt, A. R. Merritt, J. E. Merritt, and W. J. Merritt—of Duluth, Minn. Their faith in the range was the first to be rewarded. On November 16, 1890, one of their test pit crews, in charge of Capt. J. A. Nichols, of Duluth,

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struck iron ore in the NW. ¼ sec. 3, T. 58 N., R. 18 W., just north of what is now known as the Mountain Iron mine. This was followed in 1891 by the discovery of ore in the area now covered by the Biwabik and Cincinnati mines. John McCaskill, an explorer, observed iron ore clinging to the roots of an upturned tree on what is now the Biwabik property. This led to test pitting, and test pitting by the Merritts on the area of the Biwabik mine, under charge of W. J. Merritt, led to the discovery of this mine in August, 1891. The Cincinnati mine was opened the same fall. The Hale, Kanawha, and Canton mines were shown up in the spring of 1892.

The discovery of ore near what are now known as the towns of Virginia, Eveleth, McKinley, and Hibbing followed in rapid succession. The excitement following the first discovery of ore at Mountain Iron was greatly augmented by each succeeding find, and in 1891 and 1892 there was the inevitable rush of explorers.

Up to October, 1892, there were two railways touching the range, the Duluth and Iron Range, crossing the range at Mesaba station on its way to the Vermilion range, and the old Duluth and Winnipeg (now the Great Northern), reaching the range at Grand Rapids. Both of these places were far removed from the exploring centers. Most of the explorers went through Mesaba station. Reaching this place by rail, they were compelled to travel 12 to 50 miles to the west along "tote roads," which were all but impassable. The time, money, and energy needed to conduct even modest explorations at this time can be appreciated only by those who have experienced the difficulties of inland travel in the Lake Superior region away from railways. The stories of this "toting" period contain the usual records of misfortunes, lucky strikes, and enterprise incidental to a mining boom.

The railways were not long in getting into the field. In October, 1892, two lines were put in operation. The Duluth, Missabe and Northern Railway was built to connect Mountain Iron mine with the old Duluth and Winnipeg Railway (now the Eastern Railway of Minnesota, a part of the Great Northern system) at Stony Brook Junction, and later was extended to Duluth. Almost immediately after the connection with Mountain Iron a branch was sent out to Biwabik. About the same time the Duluth and Iron Range Railway sent out a branch from its main line to the group of mines at Biwabik. Very soon thereafter both railways got into Virginia.

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FIRST TRAIN LOAD OF MESABI ORE, 1892, ON DULUTH MISSABE AND NORTHERN DOCK

Reports of the discoveries of wonderful deposits of iron ore in the Mesabi district, the soft nature of the ore, its flat attitude, and the strange methods of mining it had aroused great curiosity and had started much discussion. There was a general disposition to be skeptical as to the value of the ore found in such unusual conditions and so cheaply mined. The arrival of the first train load of ore was thus a matter of much interest.

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Hibbing was reached by the Duluth, Missabe and Northern in 1893. Eveleth was reached by the Duluth and Iron Range in 1894, and by the Duluth, Missabe and Northern very soon thereafter. The Mississippi and Northern (Eastern Railway of Minnesota) about the same time projected a spur from Swan River to the Hibbing district.

With the advent of railways the development of the range went on by leaps and bounds. This marvelous development has continued to the present time. The only considerable check occurred during the period of general financial depression which the country underwent in 1894, 1895, and 1896. Almost an untouched wilderness in 1890, the district is to-day the greatest producer of iron ore in the world. The rapidity of the development of the mining industry of the district, carrying with it all the prosperity of the range, can not be better told than by the following table of shipments from the district:

Shipments from the Mesabi district.[a]

	Gross tons.
1892	4,245
1893	613,620
1894	1,703,052
1895	2,781,587
1896	2,882,079
1897	4,275,869
1898	4,613,766
1899	6,626,384
1900	7,809,535
1901	9,004,860
1902	13,329,953
Total	53,734,920

LITERATURE ON THE DISTRICT SUBSEQUENT TO ITS OPENING.

With such a phenomenal development, it is but natural that the literature on the range, published since its opening, should be voluminous. The most important reports have been issued by the Minnesota State survey.

In 1891 Messrs. N. H. and H. V. Winchell published jointly a general discussion of the iron ores of Minnesota. This was written for the most part prior to the actual discovery of ore in quantity in the Mesabi district, but it contained also a brief notice of the Merritts' discovery of iron ore near Mountain Iron in 1890. A general account of the structural relations

[a] On pp. 287–289 may be found a full table of shipments from individual mines. All figures are taken from the Iron Trade Review, except for 1902.

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of the ores of the Mesabi range was given, and a comparison with Vermilion ores. The iron formation was described and mapped as extending from Pigeon River to the Mississippi River on the west. Detailed descriptions were given of the principal explorations made up to this time, and the report was accompanied by a map showing location of iron indications in the district. A prediction was made that the Mesabi range would be found to contain vast quantities of iron ore. The first report on the Mesabi district which was written after the discovery of ore—written largely because of the discovery of ore—was published in 1893 by H. V. Winchell. This contained a map of the part of the range then productive, and a general account of the history and geology of the range. The mining developments up to that time were fully described. In 1892 Van Hise correlated the Animikie series with the Upper Huronian division of the Algonkian. In 1894 J. E. Spurr issued a bulletin containing a map of the range and a full discussion of the geology, and maintained that the ores were developed from green granules which he called *glauconite*. This was the first serious attempt to determine the origin of the ores. His conclusion that the ores are mainly derived from green granules is confirmed by the work reported in the following monograph, but his determination of the green granules as glauconite is proved to be erroneous. In 1899 was issued Volume IV of the Final Report of the Minnesota survey, containing, besides a general map of the Mesabi range and its eastern extension to Gunflint Lake, a number of detailed maps, each of them accompanied by a description of the geology, by N. H. Winchell or U. S. Grant. This volume was followed in 1900 by a volume (V) containing a general discussion of the stratigraphic relations of the rocks of northern Minnesota, including the Mesabi rocks, by N. H. Winchell. In 1901 there appeared Volume VI of the same survey, containing practically all the maps published in previous volumes of the survey, and one new one, a general geological map of the State, accompanied by synoptical descriptions.

The United States Geological Survey began field work in preparation for this monograph on July 1, 1900. While rather voluminous reports on the district above referred to had already appeared, these were different in scope and execution from the United States Geological Survey series of reports on the iron ranges, and, moreover, they contained interpretations of the geology of the area with which the United States Geological Survey

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was not in accord. It was therefore decided to map and report on the district.

In 1901, in a paper on the iron-ore deposits of the Lake Superior region, by C. R. Van Hise, there was included a preliminary report on the geology of the Mesabi district, by C. R. Van Hise and C. K. Leith, accompanied by a map of part of the district by C. K. Leith. This preliminary report contains many of the essential features of the following monograph.

In addition to the above reports there have appeared a considerable number of articles concerning the economic features of the district, some of which are listed on pages 61 and 62.

SUMMARIES OF LITERATURE, ARRANGED CHRONOLOGICALLY.

In the following summaries of literature on the Mesabi range no reference is made to a number of geological reports containing general discussions or incidental references to the general geology of northern Minnesota. Neither is any attempt made to summarize all the articles on the economic features of the Mesabi district which have appeared in the publications of engineering and mining societies and trade journals the world over. The titles of some of these articles appear on pages 61 and 62. Only such reports are summarized as mark the historical development of knowledge of the range.

The reader is likely to have difficulty in understanding some of the geological names used in reports summarized. A variety of terms have been used for the same formations, and the same term has occasionally been used with different meaning by different writers. The meaning of the names is discussed in the section on Correlation (pp. 200–205).

1810.

PIKE, MAJ. Z. M. An account of expeditions to the sources of the Mississippi and through the western part of Louisiana, performed by order of the Government of the United States during the years 1805, 1806, and 1807. Philadelphia, 1810.

A brief mention of Pokegama Falls is here made.

1832.

ALLEN, LIEUT. JAMES. Report of Schoolcraft's expedition of 1832 to the sources of the Mississippi River. American State Papers, Vol. V, Military Affairs, page 330. 1833.

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Lieutenant Allen briefly describes Pokegama Falls, and states that the river breaks through a low ridge which trends northeast-southwest. This is the first mention of the ridge which was later known as the Mesabi.

1841.

NICOLLET, J. N. Report intended to illustrate a map of the hydrographical basin of the Upper Mississippi River, made while in the employ of the Bureau of the Corps of Topographical Engineers. Twenty-sixth Congress, 2d session, 1841, Senate Document No. 237, series No. 380, p. 63.

The rocks at Pokegama Falls are briefly described and Missabay Heights are indicated on the map for the first time by Hachures.

1852.

NORWOOD, J. G. Geology of the northwestern and western portion of the valley of Lake Superior. Published in the report of a geological survey of Wisconsin, Iowa, and Minnesota, made under instructions from the United States Treasury Department, by David Dale Owen, Philadelphia, 1852, pages 213–418.

Dr. Norwood crossed the Mesabi range in two places—at Gunflint Lake and at Embarrass Lake. He reports the occurrence of iron-formation material on Gunflint Lake. Going north across the Saganaga granite, he makes the statement that this granite range, if continued in a southwesterly direction, would pass in the direction of the Missapi Wachu and Pokegama Falls on the Mississippi (p. 417).

In going up the north shore of Embarrass Lake he crossed the Mesabi range and observed syenitic granite associated with gneiss.

1855.

SCHOOLCRAFT, HENRY R. Summary narrative of an expedition to the sources of the Mississippi in 1820, resumed and completed upon the discovery of its origin in Itasca Lake in 1832, with appendices.

This contains a brief mention of Pokegama Falls.

1866.

EAMES, HENRY H. The metalliferous region bordering on Lake Superior. First Report of the State Geologist of Minnesota, St. Paul, 1866, pages 8 and 9.

In 1865 Eames crossed the "Missabi Wasju" at Embarrass Lake, and in his report mentions the granite there seen.

EAMES, HENRY H. Geological reconnoissance of the northern, middle, and other counties of Minnesota. Second Report of the State Geologist of Minnesota, St. Paul, 1866, pages 1–58.

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Eames in 1866, referring to the "gigantic uplifts" in the northern part of the State, which reach their greatest altitude "at or near Missabe Heights," states: "In this region are found also immense bodies of the ores of iron, both magnetic and hematitic, occurring in dikes and associated with the rock in which it is found. In some of these formations iron enters so largely into its composition as to affect the magnetic needle, both in its horizontal deflection and vertical dip" (p. 18).

In a geological reconnaissance Pokegama Falls and the falls of Prairie River were visited. The rock at Pokegama Falls is referred to the Potsdam. The lower or first falls of Prairie River were referred to as "an uplift of igneous and metamorphosed rocks, consisting of granite, coarse and fine, quartzite or Potsdam sandstone, and iron ore," which occurred in the following order in ascending the river:

1. Fine-grained quartzose granite.
2. Iron ore.
3. Quartzite (Potsdam sandstone).
4. Fine granite.
5. Primitive schistose rock.
6. Argillaceous slate.

Passing the first falls near the upper end of the lake on the south side, an uplift is seen 50 feet high, showing the same succession of strata as above given, beginning with No. 4 and ending with No. 1. Nos. 5 and 6 are not seen here.

The upper falls of the Prairie River cut through an uplift of granite rocks.

WHITTLESEY, Col. CHARLES. A report of explorations in the mineral region of Minnesota during the years 1848, 1859, and 1864. Cleveland, 1866.

Colonel Whittlesey gives a vague account of the northern portion of Minnesota, using the term "Mesabi" range to cover the general elevated area in the northern part of the State, including the Vermilion range. The region is referred to as "an imperfectly defined region of granite, syenite, mica slate, siliceous, and talcose rocks extending to and across the national boundary."

The quartzite of Pokegama Falls is referred to the Potsdam sandstone.

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1879.

WINCHELL, N. H. Sketch of the work of the season of 1878. Geological and Natural History Survey of Minnesota. Seventh Annual Report, 1879, pages 9–25.

Professor Winchell here tells of the occurrence of iron ore near Gunflint Lake and in Ts. 59 and 60 N., R. 14 W., and publishes two analyses of ore from range 14 (pp. 22, 23). The "Mesabi Heights" are referred to as due to drift and to hard quartzite.

1881.

WINCHELL, N. H. Geological and Natural History Survey of Minnesota, Ninth Annual Report, 1881, pages 106–109.

Professor Winchell writes of a trip down the Pike River, across the portage to Embarrass River, down the Embarrass to the dam, thence east to range 14, where pits in iron-formation material (called Gunflint beds) are reported in sections 14, 15, and 28, and other places. The magnetic character of the formation is noted.

1883.

IRVING, R. D. The copper-bearing rocks of Lake Superior. Mon. U. S. Geol. Survey Vol. V, 1883, pages 382–384.

In his famous monograph on the copper-bearing rocks of Lake Superior, Irving correlates the Mesabi iron-bearing rocks as far west as Pokegama Falls with the slates and associated iron-bearing rocks at Gunflint Lake and thence eastward to Thunder Bay, and accordingly calls them *Animikie*. In 1873 Hunt had suggested the name Animikie (Indian for Thunder Bay) for the series at Thunder Bay, and the continuity of this series westward to Gunflint Lake had been established by Bell[a] and Winchell.[b]

At the same time Irving correlates the Animikie with the original Huronian of the north shore of Lake Huron and with the iron-bearing series of the Penokee-Gogebic district. This correlation has since been accepted by Van Hise and other United States geologists, and it is the one which is used in the following report.

From this time on the Mesabi iron-bearing series (the Upper Huronian of the following report) is frequently referred to in literature as the Animikie

[a] Geol Surv. of Canada for 1872–73, by Robert Bell, pp. 92–94.
[b] Ninth Ann. Rept. Geol. Nat. Hist. Survey Minnesota, by N. H. Winchell, 1881, p. 76.

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series, although this term is given different age significance by different writers.

The petrography of the gabbro of northeastern Minnesota is fully described.

1884.

WINCHELL, N. H. The geology of Minnesota. Geological and Natural History Survey of Minnesota, Final Report, Vol. I, 1884.

The first volume of the Final Report of the Minnesota survey contains a very interesting account of the early explorations in Minnesota. The development of knowledge of the geography and geology of the State is sketched. Slight reference is made to the Mesabi district.

Following the historical sketch is a description of the general physical features of the State. The discussion of the drainage systems and divides involves the discussion of the topography of the Mesabi district. Timber, soils, glacial drift, and lakes are also discussed.

CHESTER, A. H. The iron region of northern Minnesota. Geological and Natural History Survey of Minnesota, Eleventh Annual Report, 1884, pages 154–167.

Professor Chester, of Hamilton College, in 1894, published an account of an examination of the eastern end of the Mesabi range, made in 1875 for private parties. This was the first examination of the range by a mining expert noted in literature. Coming from Duluth on the south, he struck the Mesabi range at the portage of the Embarrass, and worked northeast along the range to T. 60 N., R. 12 W. A large number of outcrops and pits were examined. The siliceous bands associated with the iron bands in the iron formation are called quartzite. Attention is called to the magnetic character of the iron ore and to the fact that the alternating iron layers are not thick or continuous. From the samples of iron ore brought back from his trip a large number of analyses were made; 44.68 is given as a fair average of the percentage of iron in the part of the district covered. This, of course, applies to iron above the level of ground water, as this is the depth to which most of the pits were sunk. Professor Chester expressed the opinion that the iron-bearing rocks of the Mesabi district bear the same relation to the Huronian rocks as do the rocks of the Penokee iron range in Wisconsin.

To the north of the magnetic schists constituting the iron formation is

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a red or pink granite forming the backbone of the Mesabi range. To the north of this ridge the rock strata are much more inclined, and consist of similar slates and quartzite, but without magnetite. The general trend is east and west, following the trend of the ridge. The second belt, the red granite, identical in appearance with that of the Mesabi backbone, is exposed on the long portage between Embarrass and Pike rivers in the southwestern part of T. 60 N., R. 15 W.

In general the reader gathers the impression from Professor Chester's report that he is not favorably impressed with the value of the iron ores from the part of the district visited by him.

WINCHELL, N. H. Geological and Natural History Survey of Minnesota. Eleventh Annual Report, 1884, pages 168–170.

Professor Winchell discusses the age of the Mesabi rocks. He classes them, with the Vermilion iron-bearing rocks, as Taconic, or Lower Cambrian, equivalent in part to the Huronian of Michigan and Wisconsin.

1885.

WINCHELL, N. H. Geological and Natural History Survey of Minnesota. Thirteenth Annual Report, 1885, pages 10–24.

Professor Winchell here describes the rocks of the Mesabi range seen in a trip across the range along the Duluth and Iron Range Railway. Gabbro is crossed at Okwanim (Allen Junction). Two miles north of here is a cut in soft reddish iron-formation material. Four miles north of Okwanim is gray granite or syenite, forming the Giants range. This is about a mile wide. Two miles to the north is red granite (Embarrass). A cross section shows Huronian, Animikie, and Gabbro rocks lying with structural conformity with one another on the syenite of the Giants range, to the north of which is shown Huronian conglomerate and greenstone, with a dip to the north of about the same degree as the dip of the strata south of the range. In a general account of the crystalline rocks in the same report Professor Winchell describes the rock succession in the Mesabi and Vermilion ranges as follows:

(1) At the top are slates and quartzites, with beds of diorite (the Animikie group). These contain the Mesabi iron ores.

(2) Soft greenish slaty schists, with lenticular masses of gneiss and diorite. These contain Vermilion iron ores near the bottom.

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(3) Conglomeratic and quartzitic slates, quartzites, and marble; perhaps contain the Vermilion iron ores.

The Mesabi ores are probably the equivalent of the Commonwealth ores of Wisconsin, with no known equivalent in Michigan.

1886.

WILLIS, BAILEY. Report of a trip on the Upper Mississippi and to Vermilion Lake, Minnesota. Tenth Census of the United States, Vol. XV, 1886, pages 457–461.

Mr. Willis briefly describes the rocks at Pokegama Falls and at the two falls of the Prairie River, and accompanies the description with a sketch map of both places.

IRVING, ROLAND D. Origin of the ferruginous schists and iron ores of the Lake Superior region. Am. Jour. Sci., 3d series, Vol. XXXII, 1886, pages 255–272.

Irving concludes that the original form of the iron-bearing rocks of the Lake Superior region was iron carbonate, and that the iron ores and associated rocks of the iron formation have resulted from the alteration of this rock by percolating waters. With reference to the Gunflint district of the Animikie ores, the statement is made that a study of slides shows "complete gradations from the unaltered carbonates to cherty and jaspery materials and even to actinolitic and magnetite schists" (p. 262). No direct reference is made to the ores of the Mesabi district.

1887.

WINCHELL, N. H. Geological and Natural History Survey of Minnesota, Fifteenth Annual Report, 1887, pages 209–399.

In this report Winchell mentions the occurrence of nontitaniferous magnetite in T. 63, R. 11 W., and Ts. 59 and 60 N., R. 14 W., and states that it is comparable to the "iron ore found at Black River Falls, in Wisconsin, and at the western end of the Penokee-Gogebic iron range on the south side of Lake Superior" (p. 216).

1888.

WINCHELL, H. V. Geological and Natural History Survey of Minnesota, Sixteenth Annual Report, 1888, pages 438–440.

Here is a brief description of Pokegama and Prairie falls. It is said that the Pokegama were formerly much higher and have been worn down in the last twenty years. The Indians call them "Kakabikag" (rocky falls). They sometimes add a diminutive, and call them the "Little Rocky Falls."

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1889.

WINCHELL, H. V. Report of field observations made during the season of 1888 in the iron region of Minnesota. Geological and Natural History Survey of Minnesota, Seventeenth Annual Report, 1889, pages 77–145.

H. V. Winchell here reports on a trip from Birch Lake southwest along the Dunka River, along the Mesabi range to the Duluth and Iron Range Railway, and back again to Birch Lake. Descriptions of numerous outcrops of the iron formation, Giants range syenite, and the gabbro are given. The magnetic character of the iron is emphasized. The contact of iron formation and syenite north of Iron Lake in the SE. ¼ of NE. ¼ sec. 35, T. 61 N., R. 12 W., is described. The iron formation rests with normal erosion unconformity upon the syenite.

At the end of the season a visit was made to Pokegama Falls and Prairie River Falls, at the west end of the Mesabi range, but no new points were noted.

WINCHELL, N. H. Geological and Natural History Survey of Minnesota, Seventeenth Annual Report, 1889, pages 5–74. See also the Animikie black slates and quartzites and the Ogishki conglomerate of Minnesota, the equivalent of the "Original Huronian." Am. Geol., Vol. I, pages 11–14. Methods of stratigraphy in studying the Huronian. Ibid., Vol. IV., pages 342–357.

The nontitaniferous iron ores of the Mesabi range are classed with the Taconic and placed as the equivalents of the Huronian of the Marquette district, the Penokee-Gogebic district, the Black River Falls schists, and the Black Hills quartzites.

1890.

WINCHELL, N. H., and WINCHELL, H. V. The Taconic iron ores of Minnesota and of western New England. Am. Geol., Vol. VI, 1890, pages 263–274.

The iron ores of Minnesota are at five different geological horizons, in descending order, as follows: (1) The hematites and limonites of the Mesabi range, the equivalents of the hematites of the Penokee-Gogebic range in Wisconsin; (2) the gabbro titaniferous magnetites near the bottom of the rocks of the Mesabi range; (3) Olivinitic magnetites, just below the gabbro in the basal portion of the Mesabi rocks; (4) the hematites and magnetites of the Vermilion range in the Keewatin formation; (5) the magnetites of the crystalline schists of the Vermilion formation. It is maintained that

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the upper iron deposits of the Mesabi and those of the Penokee-Gogebic are the equivalents of the Taconic ores of western New England.

In the fall of this year occurred the first discovery of merchantable ore in the Mesabi district. The first shipment was made in 1892.

1891.

WINCHELL, N. H. Record of field observations in 1888. Geological and Natural History Survey of Minnesota, Eighteenth Annual Report, 1891, pages 7–59.

This report was written before the discovery of ore in the district. Professor Winchell briefly describes the explorations of John Mallman 2 miles south of Hinsdale, near the Duluth and Iron Range track, calls attention to the similarity of the iron formation here with that at Gunflint Lake, and suggests that there is little likelihood of ore being found here similar to that at Tower.

There is given also a brief account of a study of Pokegama Falls and of the country to the eastward for 16 miles to Griffin's camp (the Diamond mine), accompanied by a sketch map of this area. The similarity of the iron formation to that at the Mallman camp, at Gunflint Lake, and on the Penokee range, and the difference between this iron formation and that on the Vermilion range, are emphasized.

The position of the Pewabic quartzite is left uncertain. It is considered, however, to overlie the Animikie black slate, unless there are two great quartzites. This quartzite has heretofore been made the parallel of the great quartzite that overlies the Animikie unconformably, but it is possible that it runs below it conformably. The great gabbro of the Cupriferous formation is regarded as lying below the Animikie, among other reasons, because it lies next to and immediately south of the gneiss of the Giant range without the appearance of any black slate between them, and because bowlders of characteristic gabbro, red syenite, and quartz-porphyry occur abundantly in the later traps of the Cupriferous.

WINCHELL, N. H., and WINCHELL, H. V. Iron ores of Minnesota. Geological and Natural History Survey of Minnesota, Bulletin No. 6, 1891, pages 430. With a geological map, 26 figures, and 44 plates.

This report was in part written before the discovery of ore in quantity in the Mesabi district, but was not published until afterwards. A notice of the discovery of ore is included.

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The report contains a general account of the structural relations of the iron ores of the Mesabi and Vermilion ranges. The Mesabi iron ores occur in the Taconic or Huronian, consisting chiefly of carbonaceous and argillaceous slates, but often there are siliceous slates, fine-grained quartzites, and gray limestones. Near the bottom of the formation is a fragmental quartz sandstone having an apparent thickness of 300 feet, which has been called the Pewabic quartzite. All of these fragmentals are intermingled with eruptive material. Near Gunflint Lake carbonates about 20 feet in thickness occur near the bottom of the Taconic. The authors say:

> The Taconic formation embraces a variety of ores—nontitanic magnetites at the bottom, jaspilitic hematites next above, soft hematites and titanic magnetites. These are found to constitute a well-marked belt extending from Pigeon River westward to the Mississippi River, although the titanic magnetites seem to diverge from this course and to run below the St. Louis River a few miles west from Duluth. Except the titanic magnetite of the gabbro, which is a primary constituent of the rock and is of eruptive origin, all the ores of the Taconic seem to be of chemical origin, and all, except those referable to concentration from oxidized carbonates, are due to chemical precipitation, as hydrated sesquioxides in the Taconic ocean under circumstances identical with those of the precipitation of the Keewatin hematites.

On the accompanying geological map the Laurentian, Keewatin, Pewabic quartzite, and Animikie strata are differentiated and iron indications are marked in red. Comparison of this map with that published in connection with Volume IV of the Minnesota survey (see pp. 50–52) shows it to be very crude, but it was far in advance of any previous map. The Mesabi succession is also indicated in a general cross section of northeastern Minnesota.

Descriptions are given of explorations on the Mesabi range, including the Stone mine at Mesaba (Mallman's original workings), the Mallman mine proper, in sec. 11, T. 59 N., R. 14 W., and the Diamond mine, in sec. 15, T. 56 N., R. 24 W., and the discovery of ore at the Mountain Iron mine by the Merritt brothers is chronicled.

One of the most interesting features of this report is a prediction as to the future of the Mesabi range. "The Mesabi ores are destined to play a very important part in the future development of the iron industry of the State" (p. 112). Later in the same report, just after intimation had been received of the first discovery of ore on the range, it is said, "There can be no reasonable doubt * * * there will yet be mined in the Mesabi

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range even greater quantities of hematite than have been taken from that marvel of mining districts, the Penokee-Gogebic range * * *" (p. 160).

1892.

VAN HISE, C. R. Correlation Papers—Archean and Algonkian. Bull. U. S. Geol. Survey No. 86, 1892.

In his correlation bulletin Van Hise refers the Animikie series of the Canadian boundary (the eastward continuation of the Upper Mesabi series) to the Upper Huronion, a part of the Algonkian system, and correlates it with the Animikie and the Keewatin series of western Ontario, the Upper Vermilion series of the Vermilion district of Minnesota, the Upper Marquette series of Michigan, the western Menominee series, the upper series of the Penokee-Gogebic district, the Chippewa, and Baraboo, Minnesota, and Dakota quartzites.

1893.

WINCHELL, H. V. The Mesabi iron range. Geological and Natural History Survey of Minnesota, Twentieth Annual Report, 1893, pages 111–180. See also Trans. Am. Inst. Min. Eng., Vol. XXI, 1893, pages 644–686.

Mr. H. V. Winchell here gives the most comprehensive discussion of the Mesabi iron range yet published, particularly in its western portion. It is also the first report written subsequent to the discovery of ore on the range.

The succession of the Mesabi in descending order is:

1. Gabbro unconformably on all the following	Taconic
2. Black slates, Animikie	Taconic
3. Greenish siliceous slates and cherts	Taconic
4. Iron ore and taconyte horizon	Taconic
5. Quartzite unconformable on 6 and 7	Taconic
6. Green schists of the Keewatin	Archean
7. Granite or syenite of the Giants range	Archean

The granite of the Giants range is bounded on the north by a belt of crystalline mica-schists and hornblende-schists, and on the south seems to have a direct transition into the green schists of the Keewatin. The green schist has a nearly vertical cleavage. The schists do not always follow the course of the granite range. They are unconformably covered in many places by the quartzite. The quartzite never has a high dip. Near the

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base it contains pebbles of quartz and granite, as well as jasper and greenstone. This quartzite is correlated with the Pewabic quartzite of Gunflint Lake, the Pokegama quartzite of the Mississippi River, that of Sioux Falls, S. Dak., and that of Baraboo, Wis. Conformable with the quartzite is the iron ore and taconyte horizon, the strata of which are siliceous and calcareous, and are banded with oxide of iron in beds of variable length and thickness. The ore is sometimes magnetite and sometimes hematite. To the banded jaspery chert associated with the ore the term *taconyte* is applied. The greenish siliceous slates or cherts constitute a transition stage between the rocks of the iron horizon and the black slates. There is also a considerable mixture of greenish material, apparently of eruptive origin. The greater part of the rock is a red, yellow, black, white, or green chert, sometimes having a thickness of 200 or 300 feet. It often has a peculiar brecciated appearance, having been shattered into angular fragments, and recemented by the same amorphous silica. The same fracturing is also visible in the iron ore. The siliceous slates and cherts pass upward into a carbonaceous argillite of great thickness, having a dip varying from the horizontal to 20 degrees to the south or southwest. Locally the dip is as high as 45 degrees, in which case the ore deposits lie close to the green schists. The gabbro flow is over all of the previous strata. The effect of the heat on the molten gabbro was to make the iron ore which already existed in the rocks hard and magnetic, although the magnetite in the rocks westward from Mountain Iron mine was probably too far from the gabbro to have developed in this way. There is good reason to believe that the iron ore deposits in their present condition have been principally formed since the gabbro overflow. The ore deposits occur as regular beds, which lie in almost their original positions, usually having a dip of less than 30 degrees and passing into the jaspery quartzite or taconyte in three directions, and occasionally on all sides. The theory of Irving as to the origin of the Gogebic ores is partially adopted. The quartzite is impervious to surface infiltration. The ore is regarded as produced by chemical replacement of some mineral, chiefly silica, by oxide of iron. As evidence of this, all stages of the process may be seen. Iron carbonate is found in the Mesabi rocks, but it does not appear in sufficient quantity to permit the assumption that the source of the ore was originally a carbonate. The solvent for the silica was probably carbon dioxide, and its source may have been the atmosphere, the black slates, recently decaying vegetation, or the ore deposits higher

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up the slope. The silica removed from the location of the iron ores has been added to the grains of quartz in the quartzite, has been deposited as chalcedonic and flinty silica, and has been deposited in cracks and fissures in the slate, which lies at a lower elevation, but stratigraphically above the ore. The source of the iron is believed to have been chemical and mechanical oceanic deposits, which have simply concentrated in the present situation, perhaps from rocks now completely removed by erosion. The water which brought in the iron ore to supply the place of the silica taken away in solution followed the natural drainage courses, surface and underground. The Giants range is regarded as having been uplifted at the time of the gabbro outflows, and to have been caused by them.

Brief descriptions are given of the following mines: Biwabik, Cincinnati, Canton, Kanawha and Hale, Missabe Mountain, Ohio, Lake Superior, New England, Virginia, Paddock's, Lone Jack, Wyoming, Security, Great Western, Rouchleau, McKinley, and others.

The general economic features of Mesabi iron mining are discussed, such as method and cost of mining, quantity of ore, transportation, value to the State, etc.

WINCHELL, N. H. The crystalline rocks. Geological and Natural History Survey of Minnesota, Twentieth Annual Report, 1893, pages 1–28.

Professor Winchell discusses the general age of the crystalline rocks of northeastern Minnesota.

The Animikie series lie beneath the Keweenawan and above the Keewatin rocks. The Animikie and the Keweenawan together constitute the Taconic or Lower Cambrian. This series is characterized by a great quartzite associated with the iron ores and cherts. The quartzite (Pewabic) lies unconformably on all the older rocks. It often is conglomeratic, bearing débris of the underlying formations. Within it are mingled volcanic tuffs from contemporaneous eruptions. The Pewabic quartzite includes that of Pokegama Falls, on the Mississippi River, and of Pipestone County. In the vicinity of contemporaneous volcanic disturbances its grain is fine, like jaspilite, and sometimes it has acquired a dense crystalline structure from contact with the gabbro.

BAYLEY, W. S. Actinolite-magnetite schists from the Mesabi iron range in northeastern Minnesota. Am. Jour. Sci., 3d series, Vol. XLVI, 1893, pages 176–180.

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The actinolite-magnetite-schists from the iron-bearing formation in the vicinity of Birch Lake are here described, and attention is called to their similarity to the actinolite-magnetite-schists of the Penokee-Gogebic district, described by Van Hise and Irving.

WINCHELL, N. H. Some problems of the Mesabi iron ore. Geological and Natural History Survey of Minnesota, Twenty-first Annual Report, 1893, pages 134–143. See also Am. Geol., Vol. X, 1892, pages 169–179.

There is here given a general account of the rock succession and occurrence of iron ore in the Mesabi range and a discussion of the origin of the iron ore. It is concluded:

First. The Mesabi ore is not satisfactorily explained by any theory that has yet been proposed for it, or for its equivalent (Gogebic) ore on the south side of the great lake. There are some facts that favor all of the theories that have been proposed, but they meet with opposing facts of greater import.

Second. There is but one known cause acting with sufficient force, and on a geographic area sufficiently wide, to which we can appeal for the geographic and stratigraphic distribution of this ore—and that is oceanic sedimentation. That there has been a profound change in the sediments since their origination is quite evident; but whether this change took place, in whole or in part, prior to consolidation or after it is as yet unknown; and if after consolidation it is equally unknown whether it was accomplished in Taconic or in Recent time. There seems to have been something peculiar either in the nature of the sediments of this horizon or in the influences to which they have been subjected, and this peculiarity is expressed on both sides of the Lake Superior basin.

WINCHELL, N. H. Field observations in 1892. Geological and Natural History Survey of Minnesota, Twenty-first Annual Report, 1893, pages 79–134.

Here is a brief description of the following mines: Hale, Cincinnati, Biwabik, McKinley, Missabe Mountain, Security, Virginia; the exploration of the Mesaba Syndicate Company in sec. 27, T. 60 N., R. 13 W.

Mention is made of a green dike in the iron formation in the NW. ¼ of NE. ¼ sec. 32, T. 60 N., R. 13 W.

The magnetic and siliceous nature of the ore in the eastern part of the range is again emphasized, and attention is called to the fact that this part of the range is not likely to be productive.

1894.

ELFTMAN, A. H. Preliminary report of field work during 1893 in northeastern Minnesota. Geological and Natural History Survey of Minnesota, Twenty-second Annual Report, 1894, pages 159–169.

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Mr. Elftman gives a detailed petrographical description of the actinolite-magnetite-schists of the iron formation on Birch Lake and southwestward through T. 60 N., R. 12 W. The description is accompanied by a geological sketch map of the area. In approaching the gabbro contact, augite and olivine appear intimately associated with the actinolite and magnetite of the Animikie schists. The black slates, also, in the proximity of the gabbro, are changed to quartz-biotite-schists.

The Pewabic quartzite at the bottom of the Animikie is not found east of Iron Lake. The black slates are not found east of the Dunka River.

Outcrops of the Animikie below and inclosed by the gabbro between Birch Lake and Akeley Lake have the same lithological characters and composition as the actinolite-schists at Birch Lake, and are therefore included in the Animikie.

The actinolite-magnetite-schists correspond very closely in petrographical character and origin to those in the Penokee-Gogebic series described by Van Hise and Irving.

SPURR, J. E. Preliminary report of field work done in 1893. Geological and Natural History Survey of Minnesota, Twenty-second Annual Report, 1894, pages 115–124.

Mr. Spurr describes the general features of the Mesabi range. The Giants range granite (Laurentian) is found to be intrusive in the Keewatin schists. The Keewatin schists vary in origin, some being undoubtedly igneous and some detrital. Near the contact with the granite they have been metamorphosed into hornblende and mica-schists, which have heretofore been called Coutchiching or Vermilion, and assigned to a lower horizon than the Keewatin. The Animikie rocks lie unconformably upon the Keewatin schists.

The succession and structure are represented in a north-south section across the Mesabi range, passing through the town of Mountain Iron.

SPURR, J. E. The iron-bearing rocks of the Mesabi range in Minnesota. Geological and Natural History Survey of Minnesota, Bulletin No. 10, 1894, pages 1–268. With 3 colored maps and 8 plates. See also Am. Geol., Vol. XIII, 1894, pp. 335–345.

Mr. Spurr was the first to make a systematic study of the origin of the ores, and his conclusions, published in this report, are of much interest.

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The oldest formation of the district is the Keewatin, the most common rock of which is green schist, but associated with this, especially near the granites, are hornblende-schists and mica-schists. The schists have a regional cleavage, which is nearly uniform in trend, about north 70 degrees east and nearly vertical. Next in age to the Keewatin schists is the hornblende-granite of the Giants range. This range has an average width of about 10 miles, and its direction is the same as that of the schistosity of the Keewatin rocks. The granite is intrusive in the schists, as shown by numerous fragments embedded in it, by stringers of the granite in the schists, and by the metamorphism of the schists adjacent to the granite.

Unconformably upon the Keewatin and granitic rocks is the Animikie series. The Animikie series has no marked folding, slaty cleavage, or schistose structure. The rocks of the series are in a gentle southern monocline, dipping perhaps 10 or 15 degrees east of south. This monocline has gentle undulations, with axes parallel to its dip, and in the Virginia area has been faulted. The amount of disturbance is greater adjacent to the central part of the district, where are found the Keweenawan rocks. It is probable that the weight of the Keweenawan rocks has produced a sinking in the area south of the Animikie, and that this has produced the tilting. The Animikie series may be divided into three chief members—the Pewabic quartzite, the iron-bearing member, and the upper slates. The Pewabic quartzite is a fragmental rock, indurated by the enlargement of quartz grains. It occasionally passes into a fine-grained conglomerate. The iron-bearing member is composed of peculiar rocks, presenting no resemblance to the Pewabic quartzite or to the upper slate. The upper slates are of great thickness, and have at their base an impure limestone, often dolomitized or sideritized.

The part of the iron-bearing member from Pokegama Falls to Embarass Lake is called the western Mesabi range, that from Embarass Lake to Gunflint Lake, the eastern Mesabi range, and from Gunflint Lake east, the international boundary area. The description of the iron-bearing member below applies to the western part of the district. The iron formation has a thickness varying from 500 to 1,000 feet, with an average of about 800 feet. The dip varies from less than 10 to as much as 30 degrees, the average being 10 degrees. The width of the formation varies correspondingly

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from 2 or 3 miles to less than half a mile, the average width being 1 mile. Resting upon the iron-bearing member is a great thickness of fine-grained slates, at the base of which is locally an impure dolomitic limestone. When this limestone is present the contact between the iron-bearing member and the upper slate can not be distinctly located.

The least altered phase of the iron-bearing member is a rock called taconyte, which consists of a background of cryptocrystalline, phenocrystalline, and chalcedonic silica, in which are numerous granules. These are composed of glauconite, siderite, hematite, magnetite, limonite, and cryptocrystalline silica, in the very freshest phase, the two former being predominant. One of these fresher phases showed, by analyses, about 35 per cent of siderite and 65 per cent of glauconite.

In terms of percentage of the entire rock the glauconite contains the following bases:

	Per cent.
Alumina (Al_2O_3)	1.35
Sesquioxide of iron (Fe_2O_3)	1.96
Protoxide of iron (FeO)	6.49
Lime (CaO)	.63
Magnesia (MgO)	.92
Water (H_2O)	.62
Soda (Na_2O)	.11
Potash (K_2O)	.10
Total	12.18

Since silica can not be separated from the free silica in the rock, its percentage is not known, but assigning the percentage of 50, which is the usual content of silica in glauconite, the composition of the green granules of the Mesabi iron formation, supposedly glauconite, is as follows:

	Per cent.
Silica (SiO_2)	50.00
Alumina (Al_2O_3)	5.54
Sesquioxide of iron (Fe_2O_3)	8.05
Protoxide of iron (FeO)	26.56
Lime (CaO)	2.59
Magnesia (MgO)	3.78
Soda (Na_2O)	.45
Potash (K_2O)	.41
Water (H_2O)	2.54
Total	99.92

In the freshest phase were seen, in thin section, probably detrital original grains of carbonate, recognized by their cleavage as calcite or

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dolomite. From the taconyte, by a complicated series of metasomatic changes, there have developed cherts and jaspers, which are sideritic, hematitic, magnetitic, or actinolitic, or two or more of these combined. During the process the chert and iron oxides were largely concentrated in alternating bands. The cherts and jaspers are frequently concretionary and brecciated. They have often a prismatic jointing and horizontal parting.

These transformations were caused by downward-percolating waters, carrying as the chief agents oxygen and carbonic acid, and as subordinate agents sulphuric acid and alkalies. In the changes from glauconite and siderite to the oxides there was an important shrinkage of the mass, and this has resulted in the brecciation, prismatic jointing, horizontal parting, and banding. The prismatic jointing is analogous in its formation to the shrinkage of basaltic columns of lava. The horizontal parting is caused by a later shrinkage along the least diameters of the columns formed by the prismatic jointing. The banding is due to the removal of silica and the entrance of iron along the parting.

The ore deposits rest upon the Pewabic quartzite, or upon the hard and little altered iron-bearing rock, in areas of especial weakness or disturbance, as (1) actual fault lines, (2) incipient fault lines, (3) apices of anticlinal folds and the troughs of synclines. These are places of fracture, and where abundant waters were converged often form wide areas, and therefore places where large quantities of iron were supplied. The downward-percolating water, taking glauconite or iron carbonate in solution, precipitated the iron as oxide in those places where there was an abundance of oxygen, and at the same time took the silica in solution, thus forming the ore bodies. Between those of the largest size and the small local concentrations there are all gradations. The larger deposits of ore occur where they are protected from glacial erosion on the north by a hard ridge of the Keewatin rocks, especially when the hard rocks give slight elevations on either side, so as to present a basin-like depression.

The glauconite in origin is believed to be the same as modern glauconites; that is, it has developed within foraminifera and other minute shells, as a result of a reaction between the organic matter within the shells and fine ferriferous clay. As the formation contains only a small quantity of ordinary fragmental quartz grains, it formed in water at a depth beyond

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which much of these materials was deposited. As its upper horizon grades into limestone, this indicates a further subsidence of the area, so that the distance from the shore line became so great that very little mechanical detritus was furnished, and the deposit was made up of calcareous matter.

In the eastern Mesabi district the Animikie strata are pierced and intermingled with the northern border of the Keweenawan rocks, so that their normal attitude is often much disturbed. With this change the iron of the iron-bearing member becomes largely magnetic and the silica hard and crystalline. It is concluded that the iron before Keweenawan time was here in the state of sesquioxide, and that the heat of the igneous Keweenawan rocks and the disturbances of the Animikie series produced by them are the causes of the change of the sesquioxide of iron to its magnetic form. Thus the normal process of decomposition and concentration was brought to a close, and this probably explains the poverty of this part of the district in large ore deposits.

At the base of the Cretaceous are ferriferous detrital deposits derived from the Animikie. A study of these indicates that the metasomatic processes had gone far before Cretaceous time, although they have since continued to the present time.

UPHAM, WARREN. Preliminary report of field work during 1893 in northeastern Minnesota, chiefly relating to the glacial drift. Geological and Natural History Survey of Minnesota, Twenty-second Annual Report, 1894, pages 18–66.

Mr. Upham here gives a general discussion of the general geology of northern Minnesota. The area of the Mesabi range between Hibbing and the west end of the range is shown to be occupied by the Tenth or Itasca moraine; between Hibbing and Embarrass River, by morainal material representing the merging of the Itasca moraine and the Mesabi or Eleventh moraine; eastward from Embarrass River to Birch Lake, by the Mesabi moraine.

1893-1895.

BAYLEY, W. S. The basic massive rocks of the Lake Superior region. Jour. Geol., Vol. I, 1893, pp. 433–456, 587–596, 688–716; Vol. II, 1894, pp. 814–825; Vol. III, 1895, pp. 1–20.

A detailed petrographic description of the gabbro and related rocks of northeastern Minnesota.

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1896.

VAN HISE, C. R. Principles of North American pre-Cambrian geology. Sixteenth Ann. Rept. U. S. Geol. Survey, Pt. I, 1896, page 790.

The upper series of Mesabi and its eastern equivalent, the Animikie, are correlated with the Upper Huronian division of the Algonkian (as in Bull. 86), and is placed as equivalent to the Animikie and the Keewatin series of western Ontario, the Upper Vermilion series of the Vermilion district of Minnesota, the Upper Marquette series of Michigan, the western Menominee series, the Upper series of the Penokee-Gogebic district, the Chippewa, the Baraboo, Minnesota, and Dakota quartzites, the Wisconsin Valley series, the Upper Felch Mountain series, and the St. Louis slates of Minnesota.

1898.

ELFTMAN, A. H. Geology of the Keweenawan area in northeastern Minnesota. Am. Geol., Vol. XXI, 1898, pp. 90–109, 175–188; Vol. XXII, 1898, pp. 131–149.

This report includes a detailed description of the gabbro and a brief account of the contact effect of the gabbro on the underlying rocks. The glacial history of the northern part of the State is reviewed, but no features are given in addition to those previously published by Upham.

1899.

WINCHELL, N. H., and GRANT, U. S. The geology of Minnesota. Geological and Natural History Survey of Minnesota, Final Report, Vol. IV, 1899. Illustrated by 31 colored geological plates, 48 plates of photographic views, and 114 figures.

This volume is accompanied by detail maps of the Mesabi district, a general map of the district, and maps of the counties in which the Mesabi district occurs. The county maps and the detail maps of the Mesabi are made subjects of special chapters. The maps are far in advance of anything thus far published, and are specially accurate with reference to the iron-bearing formation. While the main features of the geology are essentially the same as those given in previous reports of the Minnesota survey, there are a number of minor modifications in interpretations of the geology.

The general succession for the area west of Birch Lake is, from the top down:

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Succession of formations west of Birch Lake.

Quaternary (glacial drift)	Flat or undulating till. Terminal moraines.
Cretaceous	Shales, clays, and conglomerates.
Cabotian (lower division of Keweenawan)	Gabbro.
Animikie	Upper slates. Black slates. Taconyte (iron ore). Pokegama quartzite.
Archean	Granite (post-Keewatin). Greenstones. Mica-schists (in part in Keewatin) Pewabic quartzite and iron ore. Lower Keewatin.

Spurr's theory of the origin of the ores from the alteration of glauconite grains is accepted.

In some places the bottom of the Animikie is distinctly taconitic and ferruginous, while in others it is distinctly quartzitic and conglomeratic. The Pokegama quartzite is thus not a continuous formation and is believed to blend into the iron-formation strata in places.

The "quartzitic rocks" extending eastward from Iron Lake near the east side of range 12, and geographically continuous with the Pokegama quartzite and iron formation, are mapped and described as Pewabic quartzite.[a] The Pewabic quartzite is a rock in which grünerite, magnetite, enstatite, diallage, hypersthene, olivine, and other minerals characteristic of the gabbro contact have been developed and is supposed to have resulted from the alteration of a jaspilitic phase of the Keewatin. The altered Pokegama and Pewabic quartzites are difficult to distinguish. The Pokegama quartzite usually dips less than 25 degrees, becoming horizontal, and the Pewabic usually more than 75 degrees, becoming vertical. The Pokegama quartzite is associated with taconitic iron ore and the Pewabic with jaspilitic. The former is not known to be titaniferous; the latter is usually distinctly titaniferous. The Pokegama quartzite is never associated with the peculiar muscovadyte, but the Pewabic is never without it. The Pokegama quartzite, with its taconitic companion, is known to be overlain by the black slates of the Animikie, and occurs only westward from Iron Lake. The Pewabic quartzite is overlain and underlain invariably by muscovadyte, or by "gabbro," where the alteration was intense, and occurs only eastward from the vicinity of Iron Lake.

[a] The conclusion that the Pokegama quartzite blends into the iron formation and is replaced to the east by the Pewabic quartzite is one reached by Professor Winchell. Professor Grant, in his portions of the volume, regards the quartzite as a persistent horizon at the base of the Animikie series in the western portion of the district.

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The Keewatin rocks in the part of the district west of Birch Lake are not subdivided in the mapping, but in rock cuts along the railway in secs. 15 and 22, T. 58 N., R. 17 W., Dr. U. S. Grant observed certain coarse fragmental rocks on the basis of which he suggests a division of the Keewatin into a lower igneous portion and an upper fragmental portion (pp. 372–374).

The evidence for faulting in the Virginia area, given by Spurr, is considered inadequate.

Eastward from Birch Lake, in the gabbro, are isolated areas of banded ferruginous quartzites and olivinitic iron ores which are regarded as parts of the Animikie caught in the gabbro flow. These are found in the following locations: Just north of Muskrat Lake, in sec. 30, T. 62 N., R. 10 W.; south of Disappointment Lake, in sec. 4, T. 63 N., R. 8 W.; northwest corner of Thomas Lake, in sec. 29, T. 64 N., R. 7 W.; north side of Fraser Lake, in sec. 23, T. 64 N., R. 7 W.; in sec. 20, T. 64 N., R. 6 W.; south side of Gabbemichiganak Lake, in sec. 1, T. 64 N., R. 6 W. Similar rocks are found to the east in a belt running through Chubb, Akeley, and Gunflint lakes, but as these lakes are in the area covered by the monograph on the Vermilion district their geology is not summarized.

The petrography of the gabbro itself is briefly described.

1900.

WINCHELL, N. H. Structural geology of Minnesota. Geological and Natural History Survey of Minnesota, Final Report, Vol. V, 1900, pages 1–80, 972–1000.

This volume contains Professor Winchell's final conclusions on the general geology of northern Minnesota and the origin of the Mesabi iron ores. While much of it does not concern the Mesabi district, it is here fully summarized in order to show Professor Winchell's latest correlation of the Mesabi geology with that of adjacent areas. (See discussion of correlation, pp. 200–205.)

The ancient rocks of northern Minnesota are placed in two main systems, the Archean and the Taconic. The former is further subdivided into the Upper and Lower Keewatin, separated from each other by an unconformity. The Pewabic quartzite (see above summary of Vol. IV) also is placed with the Keewatin, but is not assigned to either of the main divisions. Overlying the Archean with strong unconformity is the Taconic, represented by Animikie and Keweenawan rocks, these divisions being

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supposed to represent respectively the Lower and Middle Cambrian of other parts of the country. The Coutchiching and Laurentian rocks before mapped as separate formations are now included within the Keewatin.

Lower Keewatin.—The Lower Keewatin comprises greenstone, with associated surface volcanics which are both subaerial and subaqueous, argyllitic slates, siliceous schists, quartzites, arkoses, "greenwackes," iron ores, and marble.

The greenstone, designated the Kawishiwin, is the oldest known rock in the State, and is supposed to represent a portion of the original crust of the earth. With its associated volcanic rocks it occurs in two main belts. The southern belt begins in the vicinity of Gunflint Lake and extends westward by way of Gobbemichigamma Lake, the Kawishiwi River, and White Iron Lake, to Tower, and indefinitely westward. The northern belt of greenstone enters the State from Hunters Island, appearing conspicuously at the south side of Basswood Lake. At Pipestone Rapids and Fall Lake it widens southward and apparently unites at the surface with the southern belt, the overlying Upper Keewatin being absent for a distance of a few miles. But farther west it is again divided by the Stuntz conglomerate, the northern arm running to the north of Vermilion Lake, west of which its extension is unknown, and the southern one running south of the lake.

The fragmental stratified rocks of the Lower Keewatin are most important toward the western part of the area of exposure of crystalline rocks. They occupy a wide area, south, west, and north of Tower. The iron ores of Tower and Ely on the Vermilion iron range occur in the upper part of the Lower Keewatin. It is probable that the immediately inclosing rock is a sedimentary one, although composed of the elements of a basic eruptive. The sediments extend south to the Giants range of granite, where they are metamorphosed to mica-schists by the granite. Toward the west they extend as far as the Mississippi River and its northern tributaries and across the Bowstring, although the drift prevents the delimitation of the belt. To the northwest they extend toward Rainy Lake, in this direction being converted into mica-schists and gneisses by the intrusion of granite; in unmodified form they are found at one point only on Rainy Lake. These fragmental rocks of the Lower Keewatin doubtless also underlie most of the central and southwestern part of the State as far as the Minnesota River. Here they dip beneath the later formations in the southwestern portion of the State, and probably occupy a wide patch in South Dakota.

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South of the Giants range they occur also, but as they are covered by the gabbro and Animikie toward the east and the drift deposits of the St. Louis Valley toward the west their geographic boundaries are mostly unknown. They appear in the central and western portions of Carlton County, where their line of separation from the Upper Keewatin is quite obscure, and in the central and western portions of Morrison County. The Lower Keewatin marble is seen at Lake Ogishke-Muncie and at Pike Rapids, on the Mississippi.

The Lower Keewatin was terminated by a period of extensive folding and intrusions of granite and basic rocks.

The Pewabic quartzite belongs with the Keewatin, but whether to the Lower or Upper Keewatin is not known. This formation includes altered quartzites and iron ores between the granite and gabbro in the immediate vicinity of Birch Lake and small patches of similar rocks in sec. 30, T. 62 N., R. 10 W.; on the south shore of Disappointment Lake; on the north shore of Fraser Lake; on the south shore of Gabbemichigamma; at Akley Lake, forming the so-called Akley Lake series extending from the west side of sec. 34, T. 65 N., R. 5 W., to the eastern part of sec. 27, T. 65 N., R. 4 W.

Upper Keewatin.—The Upper Keewatin occurs in troughs in the Lower Keewatin, particularly in one main trough the axis of which is traceable from Vermilion Lake to Saganaga Lake. The northern arm of this syncline, consisting of granites, gneisses, associated mica-schists, and in some places earlier greenstones, extends from the northern part of Vermilion Lake through Basswood Lake to the northern side of Hunters Island. The southern arm, consisting of Lower Keewatin green schists and other schists, penetrated by the granite of the Giants range, extends from Pokegama Falls on the southwest toward the northeast until cut out by the encroachment of the gabbro from the south. The Upper Keewatin consists very largely of conglomerates, but also includes graywackes, argyllites, quartzites, and jaspilites, in general coarser than those of the Lower Keewatin. Volcanic rocks are less important than in the Lower Keewatin, although still present. There is no general order of succession in the Upper Keewatin excepting that it can be said that it is in general conglomeratic at the bottom.

After Upper Keewatin time both the Lower and Upper Keewatin were subjected to another folding, the axis of which had a general parallelism with the earlier folding, with the result that the Upper Keewatin lies

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in narrow synclines in the Lower Keewatin and in places is nearly or quite vertical.

Associated with the Keewatin rocks are granites of at least two periods of intrusion, one later than the Lower Keewatin and one later than the Upper Keewatin. The later granite is believed to be represented by the higher parts of the Giants range and the Snowbank Lake granite. The earlier granite is represented by the granites at Kekequabic Lake, Saganaga Lake, Basswood Lake, Burntside Lake, Vermilion Lake, Lac la Croix, and Kabetogama Lake. The origin of the granite is discussed and the same conclusions are reached as in a previous article.[a]

The Taconic.—This is unconformably above the Keewatin rocks. It comprises the Animikie and Keweenawan divisions.

The Animikie rocks enter the State at Pigeon Point and run westward along the international boundary to the eastern part of secs. 22 and 27, T. 65 N., R. 4 W. They reappear again southwestward from Birch Lake on the northwest side of the gabbro mass, and thence continue along the south side of the Giants range, constituting the Mesabi iron series, to Pokegama Falls. The higher parts of the Animikie are best developed toward the east, while the lower parts are best developed toward the west.

The Animikie rocks comprise the Pokegama quartzite, Mesabi iron-bearing formation, and some limestone and slate, all strictly conformable with one another. The thickness is several hundred feet, sometimes reaching nearly 1,000 feet. The dip of the series is uniformly to the south, 8 to 12 degrees.

The iron-bearing formation and the Pokegama quartzite constitute the base of the formation. The quartzite in places is beneath the iron formation; in other places it is in the same horizon, and in still others is above the iron formation. Commonly the base of the Animikie is marked by a conglomerate containing débris from the underlying Keewatin rocks. This is a narrow horizon which soon graduates upward into a quartzite known as the Pokegama quartzite from its typical development near Pokegama Falls, on the Mississippi River. The thickness of the quartzite is not known to exceed 50 feet and is sometimes less than 25 feet.

Above the quartzite, or in alternating beds with it, or below it,

[a] The origin of the Archean igneous rocks, by N. H. Winchell: Proc. Am. Assoc. Adv. Sci., Vol. XLVII, 1898, pp. 303, 304 (abstract); also Am. Geol., Vol. XXII, 1898, pp. 299-310; summarized in Jour. Geol., Vol. VII, 1899, p. 194.

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appears the iron-bearing or taconyte member of the Animikie, which contains the iron-ore deposits of the Mesabi iron range. The ore is usually hematite in the western part of the range and magnetite in the eastern part.

Origin of ore.—The ore was previously supposed to have been derived from the alteration of a greenish glauconitic sand rock, but later work has seemed to show that the green sand is a volcanic sand, and that the so-called taconitic rock itself has resulted from igneous forces. This is accounted for by supposing a chain of active volcanoes to have existed where the Mesabi iron range is now found. These volcanoes yielded flows and ejectamenta to the adjacent waters, which have been modified into the various phases of the iron formation now seen. This volcanic epoch may have a deep-seated connection with the Cahotian or lower division of the Keweenawan (described later).

Above the iron-bearing member is an impure, dark-colored limestone a few feet in thickness, not exceeding 20. It extends apparently the whole length of the Mesabi range, but has been identified in two places only, sec. 7, T. 58 N., R. 17 W., and doubtfully on the shores of Gunflint Lake. This limestone may be regarded as the basal horizon of the next overlying rock.

The black slate is probably several thousand feet in thickness and constitutes the bulk of the Animikie. In the neighborhood of Gunflint Lake it has been divided by Dr. Grant into a lower black slate division and an upper graywacke-slate division, both of which members are interleaved with diabase sills.

In the Indian reservation at Grand Portage and at various places along the Grand Portage trail is a graywacke, which is supposed to overlie the black slate member, but its extent and stratigraphical position have not been satisfactorily established.

The top of the Animikie has not been identified. The first recognizable datum plane after the close of the Animikie is the Puckwunge conglomerate, supposed to be the fragmental base of the Keweenawan.

At one or two places southwestward from Birch Lake, and at Little Falls, on the Mississippi River, and in Morrison County, the Animikie has been converted into a mica-schist.

The age of the Animikie is believed to be Lower Cambrian for the

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following reasons: It grades upward into Upper Cambrian rocks, as seen on the south side of Lake Superior. The derivation of the iron ores from a glauconitic green sand indicates that large quantities of foraminiferal organisms once lived in the Animikie Ocean, and Matthew has shown the existence of foraminiferal organisms associated with the iron ore in the St. Johns group of New Brunswick. Further, the Animikie has a uniformly low dip, while the lower strata are all highly tilted. There must therefore have been a great lapse of time between the deposition of the two series.

The Keweenawan.—The Puckwunge conglomerate is taken to be the fragmental base of the Keweenawan, although certain igneous rocks which antedate it, and which, perhaps, are contemporaneous with the upper portions of the Animikie, are also called Keweenawan. The conglomerate is found at Grand Portage Island, at Isle Royale, on the Baptism River, at Little Marais, on Manitou River, at the deep well at Short Line Park near Duluth, and at New Ulm.

Above this conglomerate are conglomerates and sandstones of Keweenawan age which are stratified with lavas of diabasic nature. Still higher up the eruptive rocks become less in quantity and the fragmental rock is a sandstone, known as the Hinckley sandstone, quarried in the gorge of the Kettle River in Pine County. This in turn grades up into typical Upper Cambrian sandstones of the St. Croix Valley. The term Potsdam is restricted to the Puckwunge conglomerate and the hardened quartzites immediately overlying it, represented by the Sioux quartzite, the Baraboo and Barron County quartzites of Wisconsin, the quartzite at Grand Portage Island and west of Grand Portage village, the New Ulm quartzite in Cottonwood County, and the quartzite in Pipestone County.

The igneous rocks of the Keweenawan vary in age from late Animikie time to the top of the Keweenawan series. They are divided into two groups, the Cabotian or Lower Keweenawan and the Manitou or Upper Keweenawan.

The Cabotian division includes gabbro and contemporaneous red rock and their surface lavas, and all other dikes and sills which are associated with but are younger than the Animikie clastic rocks and which are older than the Puckwunge conglomerate. The lower member of the Cabotian is the gabbro, which covers an enormous area. It extends on the east to East Greenwood Lake, in T. 64 N., R. 2 E. On the north it is bounded by

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the Animikie strata of the Mesabi iron range. Its westernmost exposure is in the vicinity of Short Line Park, Duluth. The southern limit is irregular, swinging from East Greenwood Lake in a zigzag manner through T. 63 N., R. 1 W.; T. 62 N., R. 2 W.; T. 62 N., R. 4 W.; T. 60 N., R. 6 W.; T. 60 N., R. 7 W.; T. 58 N., R. 10 W., and T. 55 N., R. 11 W., to Duluth.

Along the northern and northwestern side of the great gabbro mass the gabbro is plainly intrusive on the older formations, Animikie and Keewatin.

From the northern border of the gabbro many sills offshoot and penetrate the Animikie strata parallel to the bedding. These are known as the Logan sills.

Near its contact with the underlying rocks, both the Animikie and the Keewatin series, there are various altered rocks which can be connected in places with the gabbro and in places with the underlying rocks. To these altered rocks the term "muscovadyte" has been applied. It includes the various so-called peripheral phases of the gabbro.

On the southern and eastern border the gabbro is penetrated by and penetrates in a confused manner the red rock, with which it alternates both structurally and areally. It is believed to have resulted from the metamorphism by the gabbro of the Animikie, and perhaps earlier fragmentals.

As the granites of the Archean are believed to have resulted from the softening of acid fragmentals, so the gabbro may have been the result of the metamorphism or re-fusion of the Keewatin greenstones.

The anorthosite masses of the Beaver Bay diabase, supposed by Lawson to be of Archean age and to underlie unconformably the Beaver Bay diabase, are believed to represent segregation phases in the main gabbro flow, and to be the same as anorthosite masses in the gabbro proper to the west.

The Beaver Bay diabase is believed to represent the upper portion of the great gabbro flow, and to be due to the first and greatest movement of the gabbro toward Lake Superior. The Logan sills belong to this part of the gabbro flow.

The Manitou division of the Keweenawan includes the surface flows, sills, and dikes which accompanied and followed the Puckwunge conglomerate. These eruptives, with the clastics associated with them, do not have a thickness in Minnesota of more than 1,000 feet. These lava sheets extend along the shore of Lake Superior from near Baptism River to near Grand

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Marais, except where replaced at intervals by the Beaver Bay diabase or some of the intersheeted fragmentals. They occur also in the neighborhood of Grand Portage Bay, but their extent here is not definitely known.

General.—The most important petrological conclusions determined from the examination of the Minnesota crystalline rocks are three in number:

1. All the granites of the Archean can be explained on the assumption that they are intrusives representing the metamorphosed conditions of clastic rocks adjacent to the observed intrusions, rendered plastic by the force of dynamic metamorphism accompanied by moisture.

2. The basic Keweenawan gabbro and its derivatives are derived from the metamorphism and complete re-fusion of the Archean greenstones and their attendants.

3. The green sand of the Mesabi iron-bearing formation appears to have resulted from a volcanic sand, and the taconite itself, from igneous forces.

Grant, U. S. Contact metamorphism of a basic igneous rock. Bull. Geol. Soc. America, Vol. XI. 1900, pages 503–510.

Dr. Grant describes the contact metamorphism caused by the great gabbro of northeastern Minnesota on the rocks with which it comes in contact. These are of particular interest as explaining the character of the iron-bearing rocks of the eastern portion of the Mesabi range. He says:

> That the great mass of gabbro at the base of the Keweenawan in Minnesota has features which indicate its intrusive rather than its extrusive nature; that one of the most important of these features is the marked contact zone along the lower or northern side of this mass; that in this zone a complete recrystallization of the strata has been effected, at times for a distance of a few hundred feet from the igneous rock, with less pronounced effects extending for a quarter of a mile or more; that the rocks resulting from the contact metamorphism of the iron-bearing member of the Animikie are peculiarly rich in minerals of the basic rocks—that is, in augite, hypersthene, and olivine; that the materials for these minerals were present in the quartz-magnetite-amphibole slates of the Animikie, and consequently that it is not necessary to consider these minerals as derived from the gabbro, and that the contact effects on some altered basic igneous rocks have been to reproduce the original mineral character of these rocks and to produce textures partially similar to true igneous rocks.

The petrography of the gabbro itself is summarized.

The above discussion is based primarily on facts observed eastward from Birch Lake.

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1901.

WINCHELL, N. H. Geological atlas, with synoptical descriptions. Geological and Natural History Survey of Minnesota. Final Report, Vol. VI. 1901.

This atlas contains the maps published with Volume V of the Minnesota survey and in addition a geological map of the State. The synoptical descriptions of the plates contain no features not given in Volumes IV and V. The mapping of the iron formation between Dunka River and Birch Lake as Pewabic quartzite is abandoned.

VAN HISE, C. R., and LEITH, C. K. The iron-ore deposits of the Lake Superior region [the part on the Mesabi district]. Twenty-first Ann. Rept. U. S. Geol. Survey, Pt. III, 1901, pages 351–370. Accompanied by a map of central portion of the district, by C. K. Leith.

This is a preliminary report on the district, containing a brief account of the essential features, more fully described in the present monograph. The first announcement is here made of the presence and distribution of the Lower Huronian and Archean series, as these terms are used by the United States Geological Survey. Spurr's conclusion that the ores have developed from a hydrous ferrous silicate is confirmed, but the original green ferrous silicate granules are thought not to be glauconite, as named by Spurr.

1902.

SPURR, J. E. The original source of the Lake Superior iron ores. Am. Geol., Vol. XXIX, 1902, pages 335–349.

After the appearance of the above report by Van Hise and Leith, Spurr restated his position, concluding—

1. That the iron ores of the Mesabi range and the varied and peculiar rock types of the iron-bearing formation are derived from the alteration and rearrangement of a sedimentary rock containing large quantities of a green hydrous ferrous silicate, in generally rounded, small, separate grains.

2. That the rocks containing iron carbonate, including the phases called cherty siderites and sideritic cherts, are one of the results of alteration of this original rock, the iron carbonate, and also a large proportion of the silica, being derived from the green silicate.

3. That the green silicate was formed largely through the agency of organic matter.

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4. That its habit, form, optical and chemical qualities mark it as belonging to the class of glauconites, and mark the original rock as a green sand.

5. That in accordance with what is known of the formation of green sand, the iron, silica, etc., of which the glauconite is composed were probably derived largely from fine land silt; in part, also, from solution in sea water.

6. That the above conclusions probably apply to most of the other Lake Superior iron ores.

For a full discussion of the literature covering the eastward continuation of the Mesabi range—that is, the area in the neighborhood of Akeley and Gunflint lakes and eastward—the reader is referred to Monograph XLV, on the Vermilion district.

ECONOMIC REPORTS.

In addition to the above reports, dealing mainly with the geology of the district, there have appeared a large number of articles on the economic features of the district, including descriptions of mines, mine methods, cost, production, transportation, etc. Below is given a list of such of these articles as are signed that have come to our notice. They are so numerous and so widely scattered in trade journals that it is certain that some have been overlooked:

BACON, D. S. Methods of working on the Mesabi iron range. Engineering and Min. Jour., Vol. LXIV, 1897, pp. 306–307.

BAILEY, C. E. Mining methods on the Mesabi range. Trans. Am. Inst. Min. Engineers, Vol. XXVII, 1897, pp. 529–536.

BRACKENBURY, CYRIL. Methods of mining on the Mesabi range. Mines and Minerals, Vol. XXI, 1900, pp. 150–152.

CHANNING, J. PARKE. Lake Superior iron ore. The Mineral Industry; its Statistics, Technology, and Trade to the End of 1894, Vol. III, 1895, pp. 375–402.

CHESTER, A. H. The iron region of northern Minnesota. Geol. and Nat. Hist. Survey of Minn., Eleventh Ann. Rept., 1884, pp. 154–167.

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CHAPTER III.

THE BASEMENT COMPLEX, OR ARCHEAN.

DISTRIBUTION.

The Archean rocks of the Mesabi district are confined to its central portion. They are found north and northwest of Nashwauk, northwest of Hibbing; north and northeast of Mountain Iron; in the southerly projection of the Mesabi range known as the "Horn," bounded by the cities of Virginia, Eveleth, Sparta, and McKinley; north of Biwabik, and eastward to near the east line of R. 16 W. With the exception of the portion of the Archean area east of Embarrass Lake, exposures are sufficiently common to allow of a fairly close determination of the boundaries. East of Embarrass Lake the mapping is based on the presence of abundant Archean fragments in the drift.

Included in the areas mapped as Archean north of Mountain Iron are several small patches of Lower Huronian rocks. Exposures are so few, they are so mixed in the same exposure with Archean rocks, and they are metamorphosed to such difficultly recognizable forms that their accurate delimitation on the general map is not possible. Their distribution, so far as worked out, is shown on a special large-scale plat (Pl. V).

KINDS OF ROCKS.

The Archean is represented by dolerites (and their altered equivalents, metadolerites or diabases), basalts (and their altered equivalents, metabasalts), diorites, peridotites(?), micaceous, chloritic, and hornblendic schists, granites, and porphyritic rhyolites. In abundance the rocks stand in about the following order: the micaceous, chloritic, and hornblendic schists, basalts, dolerites, porphyritic rhyolites, granites, and diorites. The basic rocks have commonly a green color and are usually referred to locally as greenstones or green schists. They are so intricately intermingled that they are given one color on the general map, but in the area northwest

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of Hibbing, to illustrate their complexity, they have been separately indicated on a special large-scale map (Pl. IV). The acid igneous rocks, consisting of the porphyritic rhyolites and the granites, are mapped under another color.

All of these rocks have their counterparts in other iron districts of the Lake Superior region. In the Vermilion and Crystal Falls districts, where especially well developed, Clements has described each phase in great detail. On this account the following description of the rocks of the Archean of the Mesabi district is very brief. The names used by Clements in the Crystal Falls and Vermilion districts are applied throughout. In case the reader desires to know more of the details of the petrography, he is referred to the description of the Archean rocks in Monographs XXXVI and XLV.

DOLERITES AND METADOLERITES.

The dolerites are best developed in the great area of Archean mapped as extending from Virginia eastward to beyond Biwabik, although occurring also in the other Archean areas. On the weathered surface they show varied shades of green and brown, these colors grading into dirty white or light yellow. On fresh fracture the color is characteristically some shade of green, commonly a rich dark green. The texture is typically ophitic, and varies from coarse to fine. Occasionally a luster mottling or poikilitic texture is present. Under the microscope the plagioclase feldspar is obscured by alteration products consisting largely of epidote, mica, quartz, and kaolin. The feldspar laths interlock to give the ophitic arrangement. The interstices are occupied by secondary hornblende, fine-grained feldspar, and their alteration products, mica, chlorite, and zoisite. In addition there are present minute quantities of ilmenite, sphene, and magnetite. The rock was originally a typical dolerite, but the alterations make the term *metadolerite*, or altered dolerite, appropriate for the greater mass of it.

BASALTS AND METABASALTS.

The basalts are most closely associated with the dolerites—in fact, grade into them—and, like them, occur in the greatest quantity in the great eastern area of the Archean. The conspicuous features by which the basalts are distinguished from the dolerites in the field are their fine aphanitic and porphyritic textures. Their color on fresh fracture also is

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frequently a somewhat lighter green than that possessed by the dolerites. Microscopically the basalts show much altered plagioclase-feldspar phenocrysts and occasional quartz phenocrysts in a very fine-grained, although holocrystalline, groundmass. The alterations of the feldspar are the usual ones to sericite, epidote-zoisite, and kaolin. The groundmass consists mainly of feldspar deeply discolored by an abundance of secondary minerals, including chlorite, zoisite, iron oxide, and calcite. No original augite is present and little or no secondary hornblende. The texture is sometimes of the fine, even grade known as "cryptocrystalline" or "microcrystalline," and at others the irregular mottled kind known as "micropoikilitic." With these textures may occasionally be seen a slight arrangement of the finer constituents, particularly the iron oxide or plagioclase laths (pilotaxitic texture), in such a manner as to suggest flowage lines of a lava. Rarely, also, the groundmass shows a spherulitic texture (625 paces north of the southeast corner of sec. 36, T. 59 N., R. 16 W.), and in this case there seems to be a considerable amount of quartz in phenocrysts and in the groundmass. The amygdaloidal texture is less rare. It is best seen northeast of Biwabik. The amygdules are filled with quartz and with finely fibrous minerals which are probably zeolites, the latter not infrequently so altered as to be visible only under crossed nicols. Other common structures are the tuffaceous and ellipsoidal structures, which appear to best advantage on the weathered surface. The ellipsoidal structure is typically developed north of Sparta. The ellipsoids themselves consist of basalt, and vary in diameter from a few inches to one or two feet. They are separated by narrow bands of somewhat lighter or darker basalt. The ellipsoidal structure is one supposed to have been induced in the rock when it first cooled from an extensive magma, perhaps subaqueous. A similar structure has been observed at many places in the basic igneous rocks of the Lake Superior country and has been fully described by Clements for the Crystal Falls and Vermilion districts.[a] The figures in the Vermilion monograph representing the structure in the Vermilion district would represent the structure equally well for the Mesabi district.

As in the case of the diabase, the alteration of the basalts has been of such a nature as to make the name "metabasalt" appropriate for most of the phases.

[a] Mon. U. S. Geol. Survey Vols. XXXVI and XLV.

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DIORITES.

The diorites are dark-gray or green rocks, which on weathered surfaces resemble hornblende-granite. Their principal constituents are plagioclase feldspar and hornblende, but there are alteration products, including mica, chlorite, epidote-zoisite, quartz, kaolin, etc. The texture varies from coarse to fine and from granitic to porphyritic. In the latter case the hornblendes, frequently showing enlargement, are the porphyritic constituents.

By diminution in the amount of feldspar and increase in the amount and coarseness of the hornblende present the diorites grade into coarse hornblende rocks, which consist almost entirely of coarse, stumpy, dark-green hornblende crystals with random arrangement. The interstitial material is plagioclase feldspar and is exceedingly sparse. Ilmenite, showing alteration to deeply colored sphene, is present both in the hornblende and in the matrix. The hornblende rocks differ from the diorites only in the relatively greater amount of hornblende present, and really constitute but a special phase of the diorites. They might perhaps be called "hornblendites," but these rocks usually contain a small amount of augite. They would fall under the general group of "perknites," a name recently suggested by Turner[a] for rocks consisting largely or entirely of monoclinic amphibole or pyroxene, or both.

PERIDOTITE.

Peridotite has been found in exploration work in sec. 33, T. 59 N., R. 15 W. It is not certain that the rock found in this exploration is in place and not a float from the north; hence it is but mentioned.

HORNBLENDIC SCHISTS.

The hornblendic schists are best developed in the area north of Mountain Iron, but they are found throughout the areas mapped as Archean. In typical form they are rich dark-green rocks, sometimes almost black, and show many brilliant reflections of hornblende cleavage faces. Many variations of the type are to be seen. The schist may have a rather light grayish-green color, or it may take on a yellowish color, due to the presence of a considerable amount of feldspar in the rock. The texture varies from coarse to fine. The hornblende crystals have a tendency to lie with their

[a] Jour. Geol., Vol. IX, 1901, pp. 507–511.

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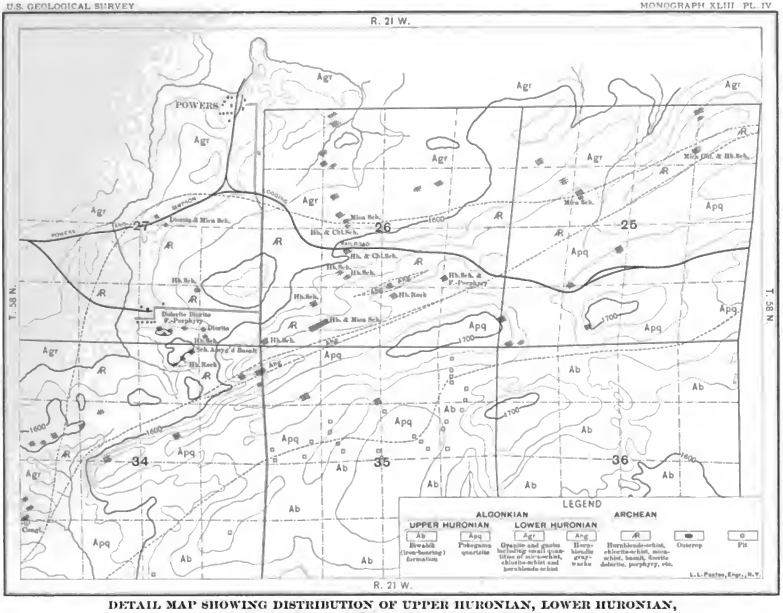

DETAIL MAP SHOWING DISTRIBUTION OF UPPER HURONIAN, LOWER HURONIAN, AND ARCHEAN ROCKS NORTHWEST OF HIBBING

Scale

0 ¼ ½ 1 mile

Contour interval 20 feet

columnar directions almost parallel, giving the rock its schistosity or cleavage. When broken with a hammer the parting of the rock parallel to the schistosity is observed not to follow a plane, but to be everywhere parallel to the columnar crystals. The pieces of the rock broken off roughly resemble in shape and dimensions the individual hornblende crystals making up the rock. Each of the pieces of rock broken off exhibits the same glistening faces of hornblende, showing that in the breaking the elongated crystals have parted along their mineral cleavage planes.

Under the microscope the hornblende appears in fresh green columnar crystals, almost certainly secondary, with a tendency to parallelism of their long axes, although many crystals are not so arranged. Rarely the hornblende appears in two forms in the same slide—in large stumpy crystals almost as wide as long and with no parallel arrangement, and in slender columnar forms with parallel arrangement. An interesting feature here is that the parallel columnar hornblendes result occasionally from the parting or slicing of the large stumpy hornblende crystals along their cleavage planes; that is, under pressure the large hornblendes have parted along their cleavage planes, yielding a large number of slices which have much greater length than breadth or thickness and have been arranged parallel.

The hornblende crystals lie in a fine-grained and much discolored matrix of feldspar, chlorite, and epidote-zoisite, these minerals showing a variety of proportions in different rocks. The usual accessory minerals, including magnetite and calcite, are to be observed.

With increase in the amount of feldspar the hornblendic schist grades into amphibolite. With increase in the amount of quartz the hornblendic schists may become almost indistinguishable from the hornblendic graywackes of Lower Huronian age which are found associated with hornblendic schists north of Mountain Iron and Hibbing (see pp. 69–70), and, indeed, it is not unlikely that some of the rocks containing considerable quartz and feldspar, here described as hornblendic schists, may themselves have been derived from the alteration of sediments. Most of the hornblendic schists, however, have unquestionably been derived from the alteration of basic igneous rocks of the Archean described above, and usually, moreover, have received their most characteristic feature through the metamorphic effect of the Lower Huronian granite. In the Mesabi

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district the actual transition from the massive basic rocks to the hornblendic schists may be observed in but few places, but along the contact between the granite and the basic igneous rocks of the Archean hornblendic schists are everywhere abundant, and in the Vermilion district to the north hornblendic schists of the same character, age, and associations may be observed in all stages of alteration from basic igneous rocks, brought about mainly and finally through the intrusion of granite.

MICACEOUS SCHISTS AND CHLORITIC SCHISTS.

These rocks may be seen throughout the Archean, but to special advantage in the great Archean area eastward from Virginia and north of Biwabik. When typically developed they consist largely of chlorite and mica, principally biotite but partly muscovite, with locally more or less talc, lying in a groundmass composed mainly of feldspar with subordinate amounts of quartz, hornblende, magnetite, ilmenite, and zoisite.

A small part of the micaceous schists has resulted from the alteration of the acid igneous rocks of the Archean, but the greater part of the micaceous schists and the chloritic schists, like the hornblendic schists, has developed from the basic igneous rocks of the Archean. Why hornblendic schists should develop in some places and chloritic and micaceous schists in others is not always known, but in general it seems to be true that the hornblendic schists are characteristic of the contact of the granite with the basic igneous rocks of the Archean, while the chloritic and micaceous schists are characteristic developments from the folding and mashing of the Archean rocks away from the granite.

GRANITE AND PORPHYRITIC RHYOLITE.

The Archean acid igneous rocks include porphyritic rhyolite, porphyritic granite, and granite. The two former may be conveniently referred to as "porphyries." Between Virginia, Sparta, and Eveleth are three small areas of Archean porphyries. The one mapped as lying mainly in sec. 22, T. 58 N., R. 17 W., is a porphyritic granite. The rock weathers white, light green, and dirty yellow. The phenocrysts of quartz and plagioclase feldspar stand in a fairly fine-grained groundmass of quartz and feldspar in which appears a considerable quantity of secondary sericite, chlorite, and quartz, indicating considerable alteration. The large, clear phenocrysts of quartz stand out like eyes. An almost identical rock has been found in the

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Vermilion iron district, and in both the Vermilion and Mesabi districts the rock has been designated in the field the "white-eyed porphyry." The mashing to which the rock has been subjected, together with the development of secondary mica and chlorite, has in places altered the porphyries to chloritic schists and micaceous schists, either kind being more or less talcose.

The porphyry mapped in secs. 16 and 21, T. 58 N., R. 17 W., and along the quarter line of sec. 29, T. 58 N., R. 17 W., is almost the same in texture and mineral content as the one just described, except that the phenocrysts, instead of being both quartz and feldspar, are plagioclase feldspar alone. Moreover, a considerable amount of secondary calcite and pyrite are to be observed in the groundmass. The rock is called a feldspar-porphyry. Like the porphyry above described, it shows much mashing, and by its alteration has yielded chloritic, muscovitic, and talcose schists.

Near the west line of sec. 25, T. 59 N., R. 18 W., is a dense dark-gray porphyry associated with hornblendic schist. Under the microscope the acid feldspar phenocrysts show zonal cloudy alterations to muscovite and kaolin. The feldspars lie in a fine but uneven grained matrix of feldspar and quartz, with a subordinate amount of muscovite, chlorite, kaolin, and zoisite.

Seventy paces north of the southeast corner of sec. 6, T. 58 N., R. 16 W., there is an exposure of biotite-granite. The surrounding rock is Lower Huronian slate and graywacke, and we have no evidence that the granite itself is Archean. However, it is a considerable distance from the Lower Huronian granite, and, on the other hand, not far from the granites and porphyries whose age is known to be Archean, and it has been mapped as Archean. Orthoclase feldspar and rather abundant quartz form the mass of the rock. With this is a liberal sprinkling of biotite and less greenish hornblende. The texture is typically granitic, although rather fine.

SEDIMENTARY ROCKS.

North of Mountain Iron and Hibbing, and westward, fragmental rocks are intricately mingled with the Archean igneous rocks (see Pls. IV and V). There is no positive evidence to show whether these rocks are Upper Huronian, Lower Huronian, or Archean. As they are closely folded with the Archean, it is probable that they are not Upper Huronian. Lithologically they resemble the Lower Huronian rocks, and hence they are

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described in connection with the Lower Huronian. Nowhere in the district have sediments been found which are demonstrably of Archean age. However, certain facts seem to show that sedimentary rocks of Archean age are actually present in the district. In the basal conglomerate of the Lower Huronian were found a few somewhat doubtful slate fragments and a single pebble of what is taken to be a fine-grained grit containing grains of quartz, feldspar, and iron oxide. While careful search has failed to reveal the counterparts of these rocks in the true Archean, it is possible that in the future they will be found. Indeed, it is not impossible that certain of the altered sediments included in the Archean and mapped as Lower Huronian may be truly of Archean age. On the other hand, the sedimentary fragments in the conglomerate of the Lower Huronian may have been brought in from distant areas and the Archean of the Mesabi district in itself lack them. It makes little difference which is the case, for it is known that beneath the Lower Huronian rocks in the Lake Superior region are other subordinate sedimentary rocks associated with what has been mapped in the past as Archean. The pebble in the conglomerate here described offers additional evidence of this fact. Whether or not small areas of these Archean sedimentary rocks be found in place in the narrow confines of the Mesabi district is a matter of small importance.

STRUCTURE.

The Archean rocks of the district, being igneous throughout, have only such structures as are characteristic of massive and schistose igneous rocks The original igneous structures have been mentioned above. While most of the Archean rocks show some cleavage, perhaps about half have enough cleavage to warrant calling them schists. In general the plane of cleavage is nearly vertical and strikes parallel to the range, about N. 60° E. The hornblendic schists north of Mountain Iron have a cleavage of a linear parallel type, and the lines of the cleavage dip steeply to the northeast. In addition to cleavage there are many joints and faults with displacements of a few inches or feet, but no regular systems have been determined.

RELATIONS TO OTHER SERIES.

The Archean rocks, both basic and acid, form a basement upon which the sedimentary rocks of the region were deposited, and hence between the Archean and the overlying rocks is a structural unconformity.

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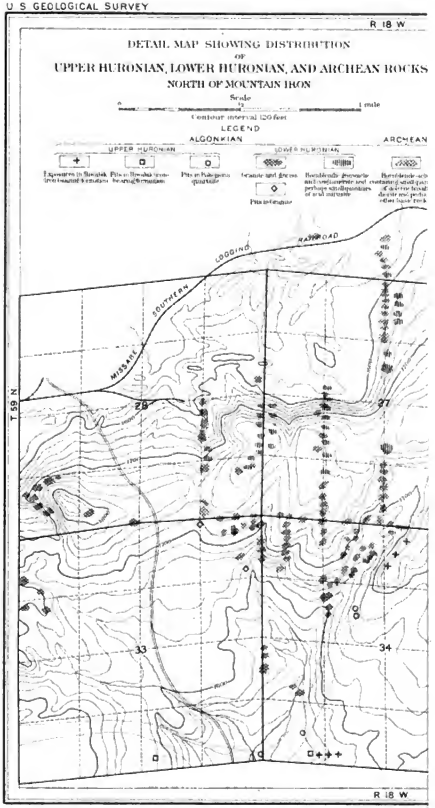
U S GEOLOGICAL SURVEY



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The sedimentary rocks now lying next to the Archean are Lower Huronian for a part of the district and Upper Huronian for another part. This results from the fact that the Upper Huronian is unconformably above the Lower Huronian and laps over the Lower Huronian onto the Archean. The Lower Huronian, near its contact with the Archean, is a coarse conglomerate, containing large pebbles and bowlders of the kinds of rocks found in the Archean, with the exception of some of the schists, which were formed by the mashing of Archean rocks subsequent to the deposition of the conglomerate. The actual contact of the Upper Huronian and Archean is drift covered, but from the known fact that the Upper Huronian is unconformably above the Lower Huronian and the Lower Huronian is unconformably above the Archean, it is certain that the Upper Huronian rests unconformably upon the Archean.

The Archean along its entire northeastern edge is in contact with granite which is intrusive into the Archean rocks. Actual contacts of the two are to be observed in a number of places, and at such places the Archean greenstones become micaceous or hornblendic.

While some of the schists are clearly the altered equivalents of the Archean igneous rocks which have yielded pebbles to the conglomerates at the base of the Lower Huronian, others of the schists have not been proved to have resulted from the alteration of Archean rocks, but are supposed to be Archean from their lithological similarity to such rocks. In spite of such similarity, some of the schists may be of Lower Huronian age. To this doubtful group belong a part of those north of Mountain Iron, northwest of Hibbing, and in Rs. 22 and 23 W.

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CHAPTER IV.

THE LOWER HURONIAN SERIES.

DISTRIBUTION.

Sedimentary rocks of Lower Huronian age appear in two considerable areas in the Mesabi district. One with an average width of perhaps a mile extends from Eveleth northeast to Biwabik; the other, somewhat less than a mile in width, extends from near the Duluth and Iron Range Railroad northeast to near the center of sec. 11, T. 59 N., R. 14 W. In the former belt there are areas of green schist forming the cores of the hills. One of them has been mapped, but others, while their presence is known by isolated exposures, are not sufficiently exposed to warrant their separation on the map. A number of small patches of Lower Huronian sediments are known also in other parts of the district, as follows: East of Biwabik, in the northern portion of sec. 1, T. 58 N., R. 16 W.; north of Biwabik, in sec. 34, T. 59 N., R 16 W.; bordering the Archean north of the Genoa mine at Sparta; northwest of Virginia, along the line between secs. 31 and 32, T. 59 N., R. 17 W.; northeast of Virginia, near the east side of sec. 34, T. 59 N., R. 17 W.; bounding the Archean north of Mountain Iron, in sec. 34, T. 59 N., R. 18 W.; intricately mixed with hornblendic schists and acid intrusives in a belt running through secs. 28, 27, 22, and 23, T. 59 N., R. 18 W. (see Pl. V); northwest of Hibbing, in a narrow belt bounding the Archean in secs. 26, 34, and 35, T. 58 N., R. 21 W., also in deep drill hole beneath quartzite 1,025 paces north, 665 paces west, sec. 35, T. 58 N., R. 21 W.; in the area mapped as Archean in secs. 19, 30, and 20, T. 57 N., R. 22 W.; and near the contact of the hornblendic schist with the granite near the north line of sec. 2, T. 56 N., R. 23 W.

Granite of Lower Huronian age forms the core of the Giants range and is exposed on its upper slopes from Grand Rapids eastward to near the east line of R. 14 W., with only one break, north of Mountain Iron, where it is interrupted for a short distance by Archean hornblendic schists. The granite thus bounds on the north the other formations for most of the district. Our detailed work has not gone farther north than the granite boundary.

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A dike of Lower Huronian porphyry appears northwest of Biwabik, in the northern part of sec. 3, T. 58 N., R. 16 W. The porphyry in sec. 25,

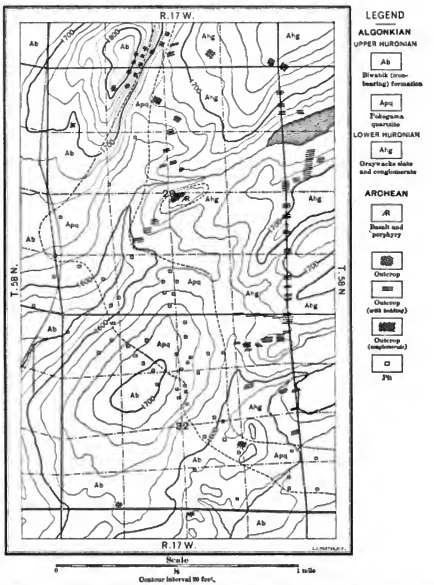

FIG. 1.—Detail map showing distribution of Upper Huronian, Lower Huronian, and Archean rocks northeast of Eveleth.

T. 59 N., R. 18 W., described on page 69 with the Archean, may be Lower Huronian, but there is no evidence one way or the other.

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KINDS OF ROCKS.

The Lower Huronian rocks are both sedimentary and igneous. The sedimentary rocks include interbedded slate, graywacke, and conglomerate, and the igneous rocks include granite and porphyry.

GRAYWACKES AND SLATES.

The following description applies to the normal phase of graywacke and slate making up the bulk of the sedimentary portion of the series. The highly metamorphosed phases caused by the metamorphism of the granite are described in a separate section.

The interbedded graywackes and slates form the great bulk of the sediments. They are dull, dark-gray and dark-green rocks which usually weather to a somewhat lighter green or gray or to a dirty light yellow. The grain is usually fine, although it varies considerably. The bedding, shown by both color and texture, is conspicuous. Parallel to the bedding a secondary cleavage has been developed. As a result of variation in texture, bedding, and secondary cleavage, there appear all gradations between metamorphosed coarse graywackes, banded graywackes, and finely fissile slates. Along the parting plane of some of the graywackes and slates may be seen glistening plates of mica or chlorite, conspicuous because of the fact that they appear in separate spangles on the dark background rather than in continuous layers, although, indeed, some of the more fissile slates show mica and chlorite in the continuous layers characteristic of slates.

Under the microscope the graywackes and slates show little uniformity in texture and mineralogical composition. A composite slide from the less altered graywackes would show angular to subangular grains of quartz and feldspar in about equal quantity and of rather uniform, small size, cemented by a sparse, ill-defined matrix of the same material, in which there is much chlorite and micaceous material and cloudy alteration products of the feldspar. While the particles are not well rounded, their general aspect leaves no doubt as to their clastic character. Certain slides show a predominance of quartz grains and others a predominance of feldspar grains. Certain slides have almost no cementing material; in others it is so abundant as to make the clastic grains look almost like phenocrysts. In certain slides, again, the matrix is almost entirely an ill-defined greenish chloritic or

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micaceous substance; in others, a fine-grained cloudy alteration of feldspar with little of this material. The chlorite and mica in the matrix are in large, distinct plates parallel to the bedding. These are the ones which appear so conspicuously on the parting planes of the graywackes above referred to.

The slates under the microscope show an exceedingly fine felty mass of quartz and feldspar almost obscured by an aggregate of micaceous and chloritic substances. In other words, they show the ordinary features of typical slates. A great variety of rocks intermediate between the graywackes and slates show microscopical features intermediate between those above described.

In certain areas iron pyrites is fairly abundant in both the slates and the graywackes. This, while occasionally fresh, is for the most part altered to iron oxide, which retains the cubic form of the pyrites, or, if altered to iron ore, is weathered out altogether, being represented only by iron-stained cavities which frequently retain the cubic form. Iron pyrites may be especially well observed in the SW. ¼ sec. 22, T. 58 N., R. 17 W.

The graywackes and slates above described have resulted from the alteration of fine mud and feldspathic sand deposits. The metamorphism has consisted in their cementation into hard rocks, which has been brought about by the recrystallization of the finer materials in the background and perhaps the infiltration of quartz from without, and by the abundant development of chloritic and micaceous materials. Some of the mica, especially that in separate clear-cut plates, may have been originally deposited in its present position, but most of it, and especially that in continuous sheets on the parting surfaces, is undoubtedly a secondary development due to dynamic movement in the rock. In general, the mashing of the rock has not been sufficient to develop any secondary structure inclined to bedding, and its main effect has been in developing micaceous minerals parallel to bedding.

CONGLOMERATES.

The conglomerates are perhaps the most interesting of the Lower Huronian sediments. They are most abundantly and typically exposed in a belt running from the cut along the Duluth and Iron Range Railroad in sec. 22, T. 58 N., R. 17 W., southwest through secs. 22 and 21

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into secs 20 and 29, T. 58 N., R. 17 W. Similar conglomerates are known in small patches bordering the greenstones north of the Genoa mine, at Sparta.

The conglomerates are massive rocks for the most part, with various shades of green on fresh surface and a lighter green on the weathered surface. The pebbles vary in diameter from 6 inches to a small fraction of an inch. In kind they are, for the most part, identical, both macroscopically and microscopically, with the rocks in the Archean above described, including diabases, basalts, and granite-porphyries. The more basic pebbles are in greater quantity than the acid ones. One of the most characteristic pebbles is a peculiar, purplish, dark-green porphyritic basalt in which the phenocrysts, originally of feldspar, are now spots of greenish chloritic material. The conglomerates have a fine-grained green matrix, which was probably originally largely of feldspar and quartz, but which is now almost obscured by chlorite and sericite alterations. The common green fragments and the green matrix of the conglomerates make the name "greenstone-conglomerate" very appropriate, and this, indeed, is what the rock has been called during the field work. In walking through the railroad cut above referred to, unless one looks very closely he is likely to suppose the rock to be an original basic igneous one. In other places many of the pebbles of the basic igneous rocks weather to a salmon pink, giving the impression that the rock is made up largely of porphyry pebbles. An examination shows that the apparently acid fragments are really basic, while the true porphyries weather grayish green and look basic.

In addition to the common pebbles above named, there appear a few pebbles of white and greenish-gray chert, which may represent altered slate (45494). Close examination of these fails to determine whether or not they are sedimentary slates, but one or two fragments are seen to have a very fine banding, which may indicate sedimentary origin. In the Duluth and Iron Range Railroad cut, also, one pebble was found which may be a fine grit or graywacke. It is a greenish-gray, fine-grained rock made up of roundish and subangular grains of quartz and much-altered feldspar in an abundant fine-grained matrix of similar materials, obscured by greenish alteration products. Throughout the rock are little specks of iron oxide. One of these appears on the weathered surface like a little fragmental

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grain of jasper, and was, indeed, the feature which first attracted attention to the pebble.

The presence of this possible sediment in pebbles in the conglomerate at the base of the Lower Huronian series may indicate the presence of still older sedimentary rocks somewhere in this area. Such an older sedimentary formation has been found in other districts of the Lake Superior region, the Vermilion and Marquette, but, with the possible exception of certain doubtful sediments north of Mountain Iron, no such rocks have been found in the Archean within the limits of this district. Further search may reveal them in small patches, but certainly they occupy no considerable areas.

In the NW. ¼ sec. 34, T. 58 N., R. 17 W., just north of the Genoa mine, patches of conglomerate may be observed in the southerly exposures of the massive Archean greenstones. On weathered surface the light-gray, green, or pink angular to subangular fragments stand out conspicuously from a dark-green matrix. On fresh fracture fragments and matrix have a dark-green color and can not be separated. They both resemble the underlying Archean basalt. The conglomerate is associated with a small quantity of banded rock of the same general character, which is probably an altered graywacke associated with the conglomerate. The rock next to the south is Pokegama quartzite, but the conglomerate has not been actually connected with the Pokegama quartzite, and because of its metamorphosed character and similarity to the Lower Huronian conglomerates of other areas it is here described.

The conglomerates, in common with the rest of the Lower Huronian rocks, have suffered metamorphism, but the extent of the alteration varies greatly from place to place. East of Mariska, in the railway cut referred to, the rocks show only recrystallization of the mineral particles, without marked development of schistosity. The alteration of the minerals is the same as that described above for the various rocks of the Archean. To the southwest of this cut the conglomerates have been much squeezed and are now very schistose. The recrystallization accompanying the squeezing has made the rocks very chloritic and micaceous, and, in many cases at least, has completely obliterated the clastic texture in the finer-grained portions. The pebbles have been elongated in the plane of schistosity (vertical and striking N. 60° E.), and on the weathered surface stand out in lenticular and

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oval forms from the finer, more schistose, and more easily eroded matrix. Rocks of this character may be traced into schistose rocks in which, in pebbles and matrix alike, nearly every vestige of sedimentary texture has been lost.

GRANITES AND PORPHYRIES (Porphyritic Granites and Porphyritic Rhyolites).

Lower Huronian granites form a continuous belt along the higher parts of the Giants range from near the east line of R. 14 W. to the west end of the district, except for a short distance north of Mountain Iron, where they are cut out by the Archean hornblende-schists. They also make up part of the shores of Birch Lake. Over this great area the granites show considerable lithological complexity. At Birch Lake the Lower Huronian granites are coarse gray and pink hornblende-granites. From the east line of R. 14 W. to the neighborhood of Mountain Iron the granites are similar to those on Birch Lake. It is noticeable that the coarser phases appear in the eastern end of this area. The hornblende varies in abundance, but is usually conspicuous. Rarely, as near the Mallman camps, the dark constituent is augite (45435) instead of hornblende, or again it may be partly biotite. The feldspar is partly orthoclase with Carlsbad twinning, partly microcline, and in small part plagioclase, and all of it shows cloudy alteration and a zonal structure indicating two stages of growth. Occasionally also it appears in porphyritic form. The hornblende is a fresh green variety. Quartz is present, but very sparsely; indeed, certain phases of the rock have so little quartz that they might perhaps be called syenites. A characteristic accessory is brown sphene, showing in places stages of alteration from ilmenite. In places the rock becomes very slightly gneissic, and immediately next to its contact with the Lower Huronian sediment it becomes very fine grained. Next to the contact of the granite with the Keweenawan gabbro on Birch Lake is a metamorphic rock resembling granite, which is described in connection with the gabbro.

From the neigborhood of Mountain Iron westward to the west end of the district the preponderating granite is somewhat finer grained than the granite to the east, possibly somewhat more gneissic, and usually of a pink color. Certain phases of this finer granite are similar to the hornblende-granite to the east, but by far the larger portion shows a considerably greater content of quartz and a smaller content of the basic minerals.

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Instead of hornblendes we have in these rocks green or brown biotite and muscovite. The feldspar is partly microline and partly orthoclase, as in the hornblende-granites, and the alteration of the feldspar is about the same. As in the hornblende-granites, also, the feldspar crystals occasionally stand out in porphyritic fashion.

Associated with these two prevailing types are dikes of exceedingly fine-grained pink granite showing very little biotite. They may be well observed in the cuts along the main line of the Duluth and Iron Range Railroad. Other dikes are pegmatitic granite consisting of a pink feldspar with very abundant quartz, and with the ferromagnesian minerals almost totally lacking. They may be seen to advantage at the upper falls of the Prairie River.

In connection with the Lower Huronian granites should be mentioned a dike of feldspar-porphyry intruding the Lower Huronian sediments just northwest of Biwabik, in the NW. ¼ of NW. ¼ sec. 3, T. 58 N., R. 16 W. It is a very fine-grained, grayish, acid rock which under the microscope shows orthoclase-feldspar phenocrysts, now much altered, lying in the usual altered matrix of quartz, feldspar, and chloritic material.

North of Mountain Iron, in sec. 34, T. 59 N., R. 18 W., near the contact of the granite, hornblende-schists, and Huronian sediments, is an exposure of a porphyritic rhyolite in which quartz and feldspar phenocrysts of about equal abundance stand in a fine-grained but holocrystalline matrix of quartz and feldspar with a spherulitic texture. There is no direct evidence to show whether the rock is Lower Huronian or Archean.

At 1,400 steps north of the southeast corner of sec. 16, T. 59 N., R. 14 W., in the Lower Huronian sediments, is a dike, about 25 paces wide, of a dark-gray, fine-grained, schistose, chloritic and hornblendic granite. The rock under the microscope is seen to consist of orthoclase feldspar showing considerable alteration to sericite, kaolin, and zoisite, which is in about equal abundance with hornblende and chlorite. The hornblende is a green variety showing little alteration and usually having crystal form. The chlorite is secondary.

In sec. 11, T. 59 N., R. 14 W., and northwestward for a mile and perhaps more is a fine-grained porphyritic rhyolite or granite which apparently is intruded by the Lower Huronian granite. As to its age, all that can be said is that it is older than the Lower Huronian granite, but

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whether Archean or Lower Huronian there is no direct evidence. Because of its close association with the granite in its distribution and its dissimilarity to the Archean porphyries, it is described in this connection rather than with the Archean. The distribution of this rock in sec. 11 is shown by the detailed sketch map (Pl. VI). The rock is gray or pink, fine grained, and contains minute red and gray streaks. Under the microscope the texture is seen to vary from porphyritic to granitic. In certain slides large feldspar phenocrysts stand in a fine-grained granular matrix of quartz with a subordinate amount of feldspar. The feldspar shows in places strain shadows, fracturing, peripheral granulation or even total granulation. In other slides the quartz and feldspar particles occur in about equal size. It is possible that the porphyritic texture may be in part the result of the granulation of a part of the constituents, leaving the remainder as phenocrysts in a granulated background. In addition to the quartz and feldspar there are present greatly varying but usually small quantities of hornblende, biotite, and chlorite. Under the microscope the similarity of this rock to the altered phases of the Lower Huronian graywacke is striking. In hand specimens, however, they may be discriminated.

INCLUSIONS IN GRANITE.

Through a considerable portion of the district, and particularly north of Mountain Iron and Hibbing and from there westward, there are found intricately mixed up with the granite, and not separable on a map of ordinary scale, small quantities of hornblendic schist, chloritic schist, micaceous schist, diorite, basalt, or diabase, or their metamorphosed equivalents. Some of the micaceous schists are the altered equivalents of the granite, and some of the diorites are also apparently genetically connected with the granite; such rocks are of Lower Huronian age. Other rocks, particularly the hornblendic schists, chloritic schists, diabases, and diorites, are intruded by the granite, and these might be either Lower Huronian or Archean. Still others, and perhaps the larger proportion, are so intricately mixed with the granite that no determination of their age can be made. Many of the phases can be duplicated in the area mapped as Archean, and indeed the line between the granite and the Archean in many places is determined by the relative abundance of these rocks. It is certain therefore that a considerable proportion of the rocks included in the granite are of Archean age.

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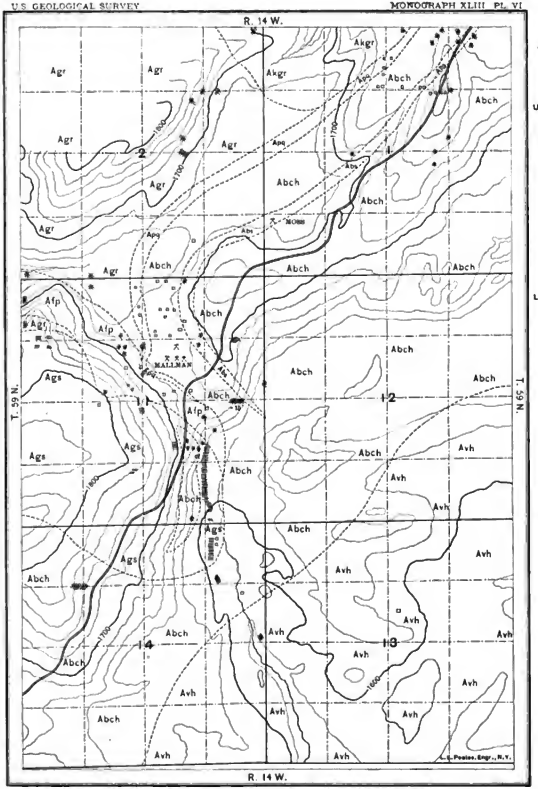

LEGEND

ALGONKIAN

KEWEENAWAN

Akgr — Granite

UPPER HURONIAN

Avh — Cordierite hornstone of Virginia formation

Abs — Interstratified slate of Biwabik (iron-bearing) formation

Abch — Ferruginous chert of Biwabik (iron-bearing) formation

Apq — Pokegama quartzite

LOWER HURONIAN

Agr — Graywacke and slate

Afp — Feldspar porphyry

Agr — Granite

Outcrop

Pit

Shaft

DETAIL MAP SHOWING DISTRIBUTION OF KEWEENAWAN, UPPER HURONIAN AND LOWER HURONIAN ROCKS IN THE VICINITY OF THE MALLMAN CAMPS

Scale

0 1/4 1/2 1 mile

Contour interval 20 feet

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PLATE VII.

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PLATE VII.

PHOTOMICROGRAPHS OF NORMAL AND METAMORPHOSED LOWER HURONIAN GRAYWACKE.

FIG. *A*.—Lower Huronian graywacke. Specimen 45412, slide 15697. From 1,300 paces north of west of the southeast corner of sec. 16, T. 59 N., R. 14 W. With analyzer, x 50. This is the normal phase of Lower Huronian graywacke, consisting of quartz and feldspar grains, mainly the former, very imperfectly rounded, and a considerable amount of secondary biotite and muscovite or sericite. All the constituents have a dimensional parallelism, and the micas have also a crystallographic parallelism. Described pp. 74–75.

FIG. *B*.—Lower Huronian graywacke. Specimen 45414, slide 15700. From 1,680 paces north of west of the southeast corner of sec. 16, T. 59 N., R. 14 W. With analyzer, x 50. This is nearer the intrusive granite contact than the specimen shown in *A*, and shows a more abundant development of the secondary minerals and a coarsening of the grain. The grain is coarser and more irregular, due to the recrystallization of the quartz and feldspar. Abundant biotite and green hornblende have developed; muscovite is nearly lacking. Abundant accessories are magnetite, ilmenite, rutile, sphene, and garnet. The rutile may be seen surrounded by and altering into sphene (titanomorphite). Described pp. 83–84.

FIG. *C*.—Lower Huronian graywacke. Specimen 45415, slide 15701. From near the southeast corner of sec. 9, T. 59 N., R. 14 W. With analyzer, x 50. This is still nearer the granite contact than the specimens figured as *A* and *B*, and shows correspondingly coarser crystallization and more abundant development of secondary minerals. The hornblende is the dominant secondary constituent, and biotite is almost lacking. The same accessory minerals are present as in fig. *B*. Described pp. 83–84.

FIG. *D*.—Lower Huronian graywacke. Specimen 45416, slide 15703. From near the east quarter post of sec. 9, T. 59 N., R. 14 W. With analyzer, x 50. The slide is cut from within an inch of the granite contact and shows the coarse recrystallization and abundant development of secondary minerals in the Lower Huronian graywacke. The feldspar shows cloudy alterations, and the quartz shows undulatory extinction. The dark mineral is almost entirely fresh, green hornblende. The accessories are sphene, rutile, ilmenite, and epidote. If this rock were found by itself and not connected by gradations with normal graywacke and slate it could not be recognized as a derivative of a sedimentary rock. Described pp. 83–84.

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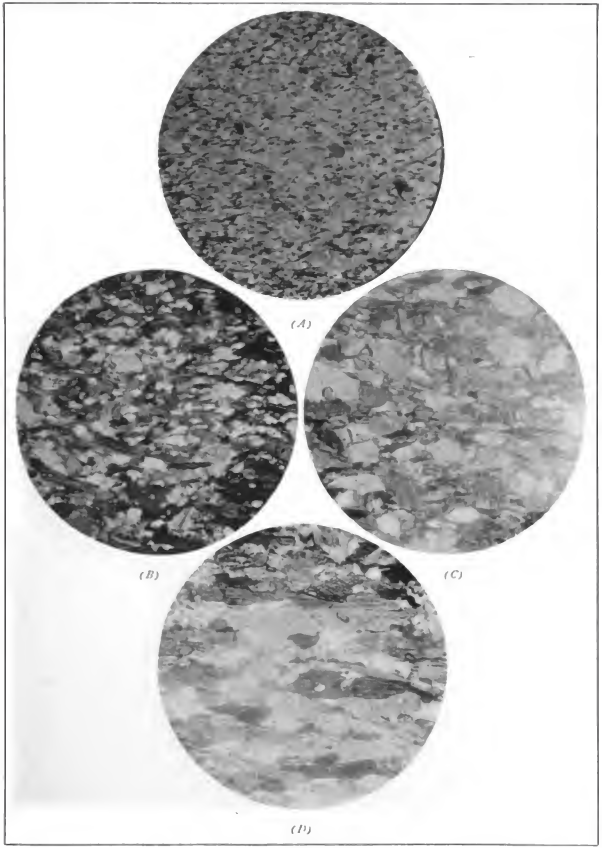

PHOTOMICROGRAPHS SHOWING PROGRESSIVE METAMORPHISM OF LOWER HURONIAN GRAYWACKE IN APPROACHING INTRUSIVE GRANITE.

THE MERIDEN GRAVURE CO.

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VEIN QUARTZ.

In both the Lower Huronian sedimentary and granitic rocks, particularly the former, there are abundant veins of quartz, resulting from infiltration along joints and brecciated zones. This vein quartz has yielded numerous and conspicuous pebbles to the conglomerates at the base of the overlying Upper Huronian series.

At the contact of the granite and the Lower Huronian series, also, there has been a segregation of quartz in irregular veins and stringers, and in this case it is believed that such quartz was in part deposited from hot solutions accompanying the intrusion of the granite.

METAMORPHISM OF LOWER HURONIAN ROCKS BY GRANITE.

The intrusion of the granite above described has further greatly metamorphosed the graywackes and slates, which are themselves the altered equivalents of muds and sands. In approaching the granite they become more chloritic, hornblendic, and micaceous, and a marked, and usually much contorted, schistosity obliterates the bedding. They become, in short, chloritic, hornblendic, and micaceous schists. The planes of parting have colors characteristic of chlorite, hornblende, and mica, and when weathered not infrequently exhibit silvery and bronzy lusters. Under the microscope the rock may be seen to have undergone extensive alteration. There has been abundant development of secondary chlorite and hornblende and a lesser development of secondary biotite and muscovite. Abundant accessories characteristic of metamorphic rocks of this nature are present. They include tourmaline, staurolite, garnet, rutile, ilmenite, magnetite, and apatite. The alteration of the ilmenite and rutile to sphene (titanomorphite) is well exhibited. (Specimen 45414.)

It is noticeable that the development of secondary minerals is greater in rocks showing more feldspar and less in rocks consisting mainly of quartz, as would be expected. Accompanying this development of new minerals there has been a recrystallization of the original quartz and feldspar, which has resulted in increasing the size of the grains and in obliterating all evidence of their clastic character as well as of bedding. Rarely, also, the quartz particles have been made to lie with their principal axes parallel to the schistosity, thus showing crystallographic as well as dimensional

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parallelism. (Specimen 45492.) In the most altered phases feldspar crystals, which are several times the size of any found in the unaltered graywackes or slates, and which have somewhat irregular outlines, stand out among smaller quartz grains, and are larger than any of the feldspars in the unaltered graywackes. Following the recrystallization there has been a considerable cloudy alteration of the feldspar. Where the original rock was mainly quartz the grain of the metamorphic equivalent is uniformly finer than the grain of the rock originally strongly feldspathic. Between and around the quartz and the feldspar are abundant fresh secondary chlorite and hornblende and less abundant mica, in general roughly parallel, but in detail following the peripheries of the quartz and feldspar grains. While the highly developed schistose structure shows that the rocks have undergone great compression, none of the mineral constituents show any strain effects whatever because of the complete recrystallization.

Starting at some little distance from the granite contact, the graywackes and slates are of the kind above described as normal for the formation. In approaching the contact the metamorphic features just described become more and more evident, until we find their typical development immediately at the contact. Were it not for the complete gradation it would not be possible from the character of the rocks to show that the highly altered schists near the granite are really of sedimentary origin and the metamorphosed equivalents of the graywackes and slates. The series of photomicrographs (Pl. VII) show how the microscopic aspect of the graywackes and slates changes in approaching the granite.

The hornblendic graywackes associated with the Archean hornblendic schists north of Mountain Iron and Hibbing correspond in all essential features with the hornblendic graywackes formed by the contact of the granite.

THE RELATIONS OF LOWER HURONIAN GRANITE TO SEDIMENTS, AND RELATIONS OF BOTH TO OTHER SERIES.

The granites are throughout intrusive into the Lower Huronian sediments. Actual intrusive contacts are to be observed in a number of places. The Lower Huronian shows the metamorphic effects of the intrusion, and near the contacts no conglomerates are to be observed. The contact of the granite and Lower Huronian sediments is well exposed northwest of

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Mesaba station in the SE. ¼ of SE. ¼ sec. 18, T. 59 N., R. 14 W., and northeast of Mesaba station 50 steps north of the east quarter post of sec. 9, T. 59 N., R. 14 W. Near the contact at the former place the graywacke is shot through and through with stringers of granite. The alternating layers of graywacke and granite in some instances vary from a fraction of an inch up to several feet. In general, the injection with the granite has been parallel to the planes of schistosity in the altered graywacke, but in a number of places the granites may be seen cutting across the schistosity. The sketch (fig. 2) shows the intricacy of the contact at this place. The contact effect of the granite on the sediments has already been described. The granite itself close to the contact becomes very fine grained, but otherwise does not differ essentially from the granite of the main mass.

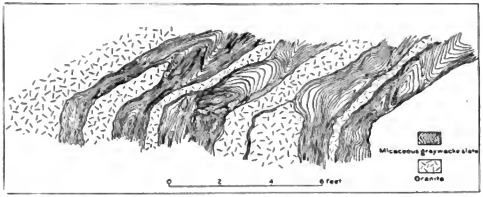

FIG. 2.—Sketch of contact of Lower Huronian granite and graywacke-slate, showing intricate nature of granite intrusion.

Another even more complex contact may be observed north of Mountain Iron, northwest of the center of sec. 34, near the Archean-Upper Huronian boundary.

While the evidence is conclusive that the great mass of the granite is intrusive into the Lower Huronian, it is not at all certain that, for limited areas, the granites here mapped and described as Lower Huronian may not contain granite of later date. The granites show great lithologic complexity, and where the points affording evidence of relation are as widely separated as they are, particularly in the western portion of the range, parts of the granite may be intrusive into the main granite mass and thus perhaps be of post-Lower Huronian date, and still no evidence of this appear. Because of the lack of exposures, it is not unlikely that even the most

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detailed field work, with this point alone in mind, would fail to delimit the later granites.

The conglomerate forming the great part of Lower Huronian sediments affords conclusive proof that the Lower Huronian sediments rest unconformably upon the Archean rocks. Every kind of pebble found in this conglomerate, with the possible exception of a few cherty slate pebbles, can be matched among the Archean rocks. The conglomerate can best be studied in the cut in the Duluth and Iron Range track east of Mariska, in the NE. ¼ of NE. ¼ sec. 22, T. 58 N., R. 17 W., and northwest of Biwabik, in the SW. ¼ of SW. ¼ sec. 34, T. 59 N., R. 16 W. At the latter place the actual contact of the two formations can be observed and the conglomerate at the base of the Lower Huronian contains pebbles identical with the adjacent Archean igneous rocks.

Both the Lower Huronian sediments and granites are unconformably underneath the Upper Huronian series, as shown both by structure and by conglomerates at the base of the Upper Huronian sediments. This unconformity is described in connection with the Upper Huronian series.

STRUCTURE.

The Lower Huronian sedimentary series shows a conspicuous sedimentary bedding. The area has been so folded that the beds now stand on edge, the dip seldom varying more than 5° or 10° from vertical. Superposed upon the original bedding structure is an excellent secondary cleavage. The cleavage planes, for the most part, are approximately parallel to the bedding planes. The strike of both bedding and cleavage is uniform, about N. 60° E., although locally varying 10° to 20° from this direction.

Both the Lower Huronian sediments and the granites are jointed, the sediments particularly so. The sediments, moreover, show conspicuous faulting and brecciation. These features may be well observed 425 paces west, 275 paces south of the northeast corner of sec. 32, T. 58 N., R. 17 W., and just south of the northwest corner of sec. 3, T. 58 N., R. 16 W. The breccias at these places might be mistaken for conglomerate, especially as at the latter place there is also present a small amount of true conglomerate (see p. 96), but they are believed to be breccias, for the following reasons: (1) The fragments are identical with the material of the

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strata adjacent. (2) The fragments are angular; certain quartz fragments are rounded, but the rounding is due to the pinching out of quartz veins; intermediate steps of the process are to be observed. (3) The interstitial material is largely vein quartz. (4) Finally, the so-called breccias occur in definite vertical zones, striking almost north and south; that is, almost directly across the sedimentary bedding. The supposed breccia grades into the unbroken strata, which have a normal strike on each side. Moreover, in attempting to match the beds on different sides of the brecciated zones it is found that there has been faulting, oftentimes as much as several feet.

THICKNESS.

As the bedding stands directly on edge, the width of the formation across the strike may measure the thickness of the series. On this basis the thickness may amount to 7,000 feet. However, the beds may represent limbs of a closely compressed fold, or perhaps several folds, which have been truncated, and in such a case the apparent thickness of the series is much greater than the true thickness. Large areas of the formation are not exposed, and while there is no positive evidence of duplication of beds the probability is that they are duplicated. In view of this probability, 3,000 to 5,000 feet is probably as great a thickness as can safely be assigned to the Lower Huronian sediments of the Mesabi district.

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CHAPTER V.

THE UPPER HURONIAN SERIES.

The sedimentary rocks of Upper Huronian age occupy practically all the southern slopes of the range from one end of the district to the other, and extend also an unknown distance south beneath the glacial drift. The surface width of the series in the area included in the district described varies from less than 1 mile to 5 miles or more. The beds of the series have a flat dip to the south. Their upper edges being truncated, they appear in belts winding along parallel to the range, the northerly belts representing the lower beds and the southerly belts the higher beds of the series.

The exposures of the Upper Huronian, particularly on the lower slopes, are so widely separated that the mapping of the series would have been an impossibility had it not been for numerous test pits sunk in search for ore, which were bottomed in the Upper Huronian series. These are particularly numerous along the central portion of the range, and have enabled the distribution of the Upper Huronian rocks to be indicated within rather close limits for this part of the range.

The Upper Huronian series comprises from the base up (1) the Pokegama formation, consisting mainly of quartzite, but containing also conglomerate at its base; (2) the Biwabik formation, consisting of ferruginous cherts, iron ores, slates, greenalite rocks, and carbonate rocks, with a small amount of coarse detrital material at its base; and (3) the Virginia slate. Between the Pokegama quartzite and the Biwabik formation there is a slight erosion interval. The Biwabik formation grades conformably into the Virginia slate both vertically and laterally. In all previous geologic work on the district the detrital rocks forming the base of the iron formation (quartzite and conglomerate) have been considered a part of the Pokegama formation, the presence of the slight break between such detrital rocks and the underlying Pokegama formation having been overlooked. On the accompanying geologic map, also, the

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basal detritals of the iron formation have been included in the Pokegama quartzite. This is done for the reasons that: (1) The layer of basal iron-formation fragmentals for the most part is so thin that it can not be indicated on the general map without exaggeration; (2) in much of the district exploration has not been sufficient near the boundary of the iron formation to allow of the discrimination of the quartzite and conglomerate

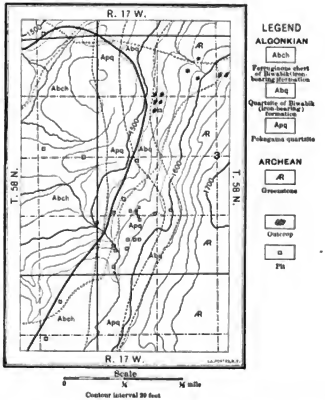

FIG. 3.—Detail map of sec. 3, T. 58 N., R. 17 W., showing separation of quartzite at the base of the Biwabik formation from the Pokegama quartzite. (A correction of this map is shown on Pl. II.)

of the iron formation from that belonging with the Pokegama formation; (3) for economic purposes it is more desirable to indicate the boundary between the possible iron-bearing area and quartzite, regardless of the formation to which the latter belongs, than between the two structural geologic units. In order to show that discrimination between the Pokegama quartzite and the detrital material at the base of the iron formation is possible where exploration has been sufficient, a detailed map has

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been made of a part of sec. 3, T. 58 N., R. 17 W. (fig. 3), where the relations of the Pokegama quartzite and the iron formation were first satisfactorily worked out. While, for the reasons stated above, all the detrital material at the base of the iron formation has been included in the Pokegama formation on the general map (Pl. II), the description of the Biwabik formation on a subsequent page includes the detrital material belonging with it.

SECTION 1. THE POKEGAMA QUARTZITE.

DISTRIBUTION.

The Pokegama quartzite is the basal formation of the Upper Huronian series. Because of the southerly dip and truncation of the series, the quartzite appears as a belt immediately south of and contiguous to the Lower Huronian and Archean formations. The belt, varying from a few steps to a half mile or more in width, extends from the west end of the Mesabi district continuously to north of Mountain Iron. From here on to the east end of the range data are insufficient for mapping the quartzite as a continuous belt, and it is accordingly mapped as a number of discontinuous areas of varying width and length. It is possible that future exploration will result in extending and connecting some of these areas, but it is also certain that some of them are really cut off from one another because of the overlapping of the iron formation. The typical Pokegama quartzite is exhibited in exposures at Pokegama Falls, on the Mississippi River; at Prairie River Falls (fig. 4), north of the Arcturus mine in sec. 13, T. 56 N., R. 24 W.; north and northwest of Hibbing; near the south quarter post of sec. 20, T. 53 N., R. 17 W.; at the east end of the range in secs. 29 and 32, T. 60 N., R. 13 W.; and test pits and drill holes have been bottomed in the quartzite at many intermediate points.

KINDS OF ROCKS.

The Pokegama formation comprises vitreous quartzites of various colors and textures, micaceous quartz slates, and conglomerates.

QUARTZITE.

The bulk of the Pokegama formation is a vitreous quartzite. Bedding is well marked by alternating light and dark bands, and rarely ripple marks may be observed. The quartz grains are well rounded, of medium size,

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and in general are better rounded and coarser than in the Lower Huronian graywackes. The colors are dark green, grayish green, light yellow, or

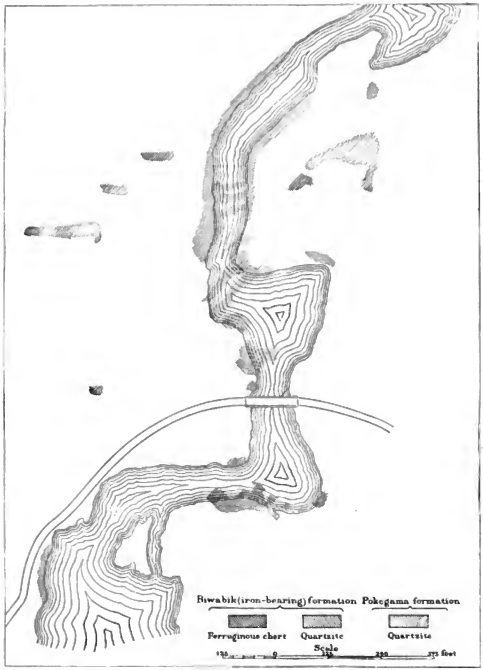

FIG. 4.—Sketch showing distribution of Biwabik and Pokegama formations at the lower falls of Prairie River.

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various shades of red and brown. In some cases at least the original colors have been yellowish and grayish green, and the red and brown colors have resulted from the infiltration of ferric iron and from the oxidation of ferrous compounds in the matrix of the quartzite. At Pokegama Falls the quartzite, for some feet from the surface, has a reddish color, but where blasted out near the dam the red colors are seen to give way a few feet from the surface to the grayish or yellowish ones. In cracks and crevices the iron staining has penetrated much deeper. In other rocks the yellow or red colors are due to numerous grains of iron oxide, mainly limonite, associated with the quartz grains. Weathering has not only discolored the quartzite, but has caused it to disintegrate to a certain extent by softening the cementing material. This phenomenon may also be observed at Pokegama Falls.

Under the microscope the quartzite is seen to be made up of well-rounded, sometimes subangular, grains of quartz and an occasional grain of microcline feldspar. In the proportion of quartz and feldspar the quartzite differs from the Lower Huronian graywackes, in which the feldspar and quartz are in about equal abundance. The fragmental grains show at places considerable effects of pressure by their undulatory extinction and cracking, but seldom are these effects conspicuous. More frequently are the grains cloudy, due to the inclusion of minute specks of other minerals. It is a noticeable fact that the clastic grains in the finer quartzites are less well rounded than in the coarser ones.

Among the quartz grains there appears here and there a granule of iron oxide, mainly limonite, which in some cases seems to have partially or wholly replaced quartz grains and in others is mixed with a greenish or yellowish chloritic substance in such a way as to suggest that it may have replaced a granule of some mineral containing ferrous silicate. The appearance and distribution of some of the iron oxide grains strongly suggest their development through the alteration of iron pyrites in an originally pyritiferous quartzite, but while such development is probable, no direct evidence of it has been observed.

The cementing material may be (1) quartz which has grown out in optical continuity with the original grains, containing abundant iron oxide and chloritic discolorations, or (2) a confused aggregate of greenish material which, with a high power, is found to be mainly chlorite, with subordinate amounts of actinolite or grünerite, quartz, and feldspar. The green matrix

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may be so abundant as to make the rounded clastic quartz grains stand out from it like phenocrysts, or it may be sparse and give way to the discolored quartz cement formed by the enlargement of the quartzite grains. The oxidation of the ferrous iron in the chloritic cement in certain of the rocks, particularly the weathered ones, has yielded red and brown hematite, which has imparted to the cement a red or brown color. In other rocks iron oxide has been infiltrated from above, discoloring the cement in the same way. Comparing the slides with the hand specimens, it is seen that the color of the quartzite, as would be expected, is due to the nature of the cementing material. Where the cement is mainly quartz formed by the enlargement of the clastic grains of quartzite the rock is one of the lighter colored gray or yellow ones. Where the cement is an abundant chloritic substance the quartzite is dark gray or dark green. Where considerable hematite has been infiltrated or developed by alteration the quartzite has distinctly reddish or brownish colors.

The dark-green and dark-gray quartzites, with an abundant chloritic matrix, are similar in general aspect to graywackes, but the clastic feldspar grains are too few to warrant the application of this name. The chloritic cement in the quartzite has been particularly studied because of its close resemblance to the green ferrous silicate occurring in granules in the overlying iron formation. It is indeed possible that a very small part of the material here called chlorite may in reality be a ferrous silicate corresponding to that described in the iron formation on a subsequent page, but no positive evidence of this has been found, and, on the contrary, positive evidence of the chloritic nature of most of it is at hand.

Where the Pokegama quartzite is in direct contact with the basic igneous rocks of the Archean it takes on a character different from that normal to the formation. In sec. 33, T. 59 N., R. 15 W., for instance, the particles, instead of being well-rounded quartz grains, are complex grains derived from the breaking down of the fine-grained underlying basalt, and both fragments and matrix are much discolored by green chloritic and hornblendic alteration.

MICACEOUS QUARTZ-SLATE.

Closely associated with and interbedded with the massive quartzites above described are thin-bedded slaty quartzites, or quartzitic slates, with a considerable amount of mica and excellent parting along bedding planes.

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They are very different in appearance from many of the quartzites, and were they not actually observed to grade into and to be conformably bedded with the quartzites at a number of places they would scarcely be referred to the same formation on lithologic grounds. They usually, though not always, overlie the massive quartzite. This may be well observed just northeast of Prairie River Falls (see fig. 4) and just southwest of the center of sec 18, T. 59 N., R. 14 W. The color varies from dark greenish gray to a light yellow or pink or red. The red and pink colors are frequently due to the infiltration of iron oxide from above along bedding planes. The texture varies from that of a medium-grained quartzite to that of a rather coarse shale. The conspicuous features of the rocks are their excellent parting parallel to bedding planes and the mica plates on the parting plane. For the most part the parting planes are smooth, with slight ridges roughly resembling fine ripple marks, but not uncommonly they are somewhat rough and contorted. On these surfaces the mica does not form a continuous layer, but appears in separated plates, each with its own twinkling reflection.

Under the microscope the quartz-slates are seen to be finer grained than the quartzites described above. The grains are more angular; the interstitial chloritic aggregate is more uniformly present; evidence of enlargement, while present, is not so conspicuous as in the quartzite; and, finally, the quartz-slates possess mica, while the quartzites do not. The fragmental grains in the quartz-slate are mainly quartz and rarely microcline, as in the quartzite, and the green chloritic material is of the same nature. Only rarely are the effects of pressure to be observed. The mica is in separate flakes, with their greater diameters parallel to the bedding, as are also the longer diameters of the quartz grains. It resembles in its occurrence the clastic mica plates sometimes seen in a sedimentary rock demonstrably unaltered. In a few cases where the quartz-slate gives evidence of having undergone much squeezing and alteration the mica is much more abundant and clearly secondary, and in such cases it has a tendency to form continuous layers along the parting planes rather than to occur in isolated flakes with definite outlines.

CONGLOMERATES.

From a structural standpoint the conglomerates are the most interesting rocks of the Pokegama formation. They form a very irregular layer but a few feet thick at the base of the quartzite.

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In the SE. ¼ of SE. ¼ sec. 18, T. 59 N., R. 14 W., the conglomerate is in several small patches overlying both the Lower Huronian graywacke and slate and the Lower Huronian granite. The next rocks to the south are of the iron formation, and although there is no evidence of Pokegama quartzite occurring in this immediate vicinity, there is plenty of room for it, and it is known less than a half mile to the northwest. There is thus reason to believe that future exploration may show it here, but whether or not the quartzite or the iron formation immediately overlies the conglomerate at this point, the conglomerate is basal to the Upper Huronian, and thus should be described at this place. A few steps west and north of the southeast corner of sec. 18 the conglomerate can be observed in a thin layer mantling over the Lower Huronian slate and graywacke. Neither the bedding of the conglomerate nor that of the underlying graywacke or slate is clear, but so far as any structure is present in either it is a horizontal one in the conglomerate and a vertical one in the lower series. The pebbles of the conglomerate are fairly small, sometimes reaching a size of 2 or 3 inches, but commonly being an inch or less. The most conspicuous fragments are white, gray, or black vein quartz, but these are scarcely more abundant than pebbles of graywacke and slate identical with those of the underlying Lower Huronian series. With these abundant pebbles are a few scattering and doubtful pebbles of granite. At 425 steps north and 460 west of the southeast corner of sec. 18 is again a thin layer of conglomerate mantling over the Lower Huronian granite. Only a short distance away the granite is found intrusive in the Lower Huronian sediments, and hence the Upper Huronian age of the conglomerate is unquestionable. Here the conglomerate contains pebbles and bowlders up to 2 feet or more in diameter, consisting of graywacke and slate, white, gray, or black chert, granite identical with that immediately underlying, and in addition pebbles of a fine-grained granite similar to that sometimes seen in dikes in the Lower Huronian granite. Certain pebbles of doubtful character may represent basic igneous rocks. The matrix is a quartzite in which the quartz grains are well rounded and set in a dark greenish- or purplish-black matrix, discolored by chloritic substances. In general the conglomerates described in this area contain a typical assemblage of pebbles and bowlders representing the various phases of rock found in the immediately underlying Lower Huronian.

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A little southwest of the center of the NW. ¼ of SW. ¼ sec 33, T. 59 N., R. 15 W., is a pit which has passed through quartzite and conglomerate into Archean basalt. The conglomerate is a much metamorphosed one, containing basalt pebbles identical with the basalt below. The conglomerate is thus unconformably upon the Archean, and is basal to the quartzite.

Near the powder house, in the NW. ¼ of NW. ¼ sec. 3, T. 58 N., R. 16 W., is a thin film of conglomerate on the upper surface of the southernmost exposure of Lower Huronian slate and graywacke. The next rock to the south is the Pokegama quartzite. The conglomerate is composed mainly of vein quartz and slate, with a few feldspar porphyry pebbles. The vein quartz and porphyry pebbles are well rounded, while the slate fragments are angular. It is believed that this may be a part of the conglomerate at the base of the Pokegama quartzite. However, just to the north and northwest, in the Lower Huronian area, are certain breccias (see pp. 86–87) which are almost identical with the conglomerate except that the fragments are not so well rounded. It is not impossible that this supposed conglomerate may be, in part, a breccia, although much of it certainly is not.

On the road a little north and a little east of the northeast corner of sec. 3, T. 58 N., R. 16 W., in the drainage ditch close to the Biwabik mine, is an obscure conglomerate in contact with the Archean green schists. The rock is reddish, and the fragments, as nearly as can be made out, are of green schistose rocks like those of the Archean subjacent, but very much altered. The rock immediately to the south is the Pokegama quartzite.

Just north of Roberts mine at McKinley are pits which have passed through Pokegama quartzite and conglomerate into Lower Huronian graywacke and slate. The conglomerate at the base of the Pokegama contains pebbles of the graywacke and slate below.

North of Mountain Iron, just northwest of the center of sec. 34, T. 59 N., R. 18 W., are small patches of conglomerate intricately mixed up with the Archean and Lower Huronian rocks which come together at this point. (See Pl. V.) The Upper Huronian rocks occur just to the southeast across a little valley. The older rocks show much intricacy of structure, erosion has consequently cut down into them unequally, and finally some of the contacts are drift covered, so that it has been exceedingly difficult to determine the true relations of the conglomerate and the adjacent rocks.

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However, there appear to be here Archean hornblende-schists and Lower Huronian graywackes and slates, and both of these are intruded by Lower Huronian granite. On top of this complex are patches of conglomerate containing well-rounded pebbles of white weathering slate and graywacke, reaching a size of several inches, and resembling the Lower Huronian sediments near at hand. A few doubtful pebbles may be Archean igneous rocks. No granite pebbles were observed. The matrix is a well-bedded graywacke, much contorted, of dark-green or dark-gray color, with mica plates on bedding planes. It seems likely that the conglomerate is basal to the Upper Huronian. But there is a distinct possibility that the conglomerate after all is basal to the Lower Huronian sediments, and that the pebbles of sediments observed are from the Basement complex. This possibility is suggested by the similarity in appearance of the matrix of the conglomerate to the typical Lower Huronian graywackes close at hand and by the absence of Lower Huronian granite pebbles.

In secs. 25 and 26, T. 58 N., R. 21 W., north of Hibbing, are large bowlders of conglomerate in the drift. They are found just south of the northern boundary of the quartzite and were undoubtedly carried there by the glaciers from this boundary. They are similar to the conglomerates north of Mesaba station, their principal pebbles being graywacke and slate, vein quartz, and granite, and in addition there are seen fragments of chlorite-schists and mica-schists similar to these rocks in the Lower Huronian and Archean areas adjacent.

On the west line of sec. 34, T. 58 N., R. 21 W., on the south escarpment of the southernmost exposure of Lower Huronian granite, is a conglomerate with pebbles up to 4 or 5 inches in diameter of vein quartz, white, gray, brown, and reddish, and of granite identical with that of the solid ledge underneath. As usual the fine quartz pebbles are the most conspicuous.

At 1,200 steps south and 400 west of the northwest corner of sec. 3, T. 56 N., R. 23 W., is a conglomerate lying on the eastward-facing escarpment of the granite, that is, between the granite and the Pokegama quartzite. The pebbles are several inches in diameter. They consist of granite identical with that beneath, of vein quartz and of jasper. The vein quartz is very abundant and forms the most conspicuous pebbles. Certain of the pebbles are somewhat discolored by iron. One ellipsoidal pebble, with a greater diameter of 3 inches, seems to be a true, bright-red,

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slightly banded jasper. It is not impossible that this represents a very highly iron-stained phase of the vein quartz so conspicuous in the pebbles, but on this basis it is difficult to account for the banding. A careful examination in the laboratory, both microscopic and macroscopic, leaves little doubt that the rock is a true jasper, that is, one of the phases of rock commonly associated with iron ore. Jasper has not been found in the lower Huronian or Archean of this district, but it occurs abundantly in this series in other districts, and this particular pebble may have come from a very considerable distance. On the other hand, it is not impossible that future exploration may show small areas of jasper in the Lower Huronian of this district.

In general, throughout the range the conglomerates which can safely be assigned to the base of the Pokegama quartzite or Upper Huronian vary only in relative abundance of the different kinds of pebbles. At every locality the pebbles are predominantly like the immediately subjacent rocks. The striking feature of the conglomerates throughout is their large content of vein-quartz pebbles. This feature was at first troublesome, but search in the underlying rocks of the Lower Huronian has shown abundant vein quartz from which the pebbles could be derived. The vein quartz being hard, massive, and homogeneous, is not likely to be so much broken up as the granites and sediments during the time it is worked over by water, and, for the same reason, fragments become better rounded. The few chert fragments and the one true jasper fragment found in the conglomerate have not yet been duplicated in the underlying rocks.

STRUCTURE.

The Pokegama quartzite in its lower and middle horizons shows but a faint bedding. In higher horizons the bedding is well shown by alternation of light and dark and coarse and fine bands, parallel to which is an excellent parting. The parting planes are made conspicuous by spangles of clastic mica. As a part of the Upper Huronian, the Pokegama quartzite has participated in the general tilting and cross folding to which the series as a whole has been subjected, and thus lies with a gentle flat dip to the south, with gentle cross folds whose axes are transverse to the range. (See structure of the Upper Huronian, pp. 178–180.) Aside from the tilting and general cross folding, the Pokegama quartzite has suffered little deforma-

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tion. Joints, while present, are inconspicuous, and little or no secondary cleavage has been developed in the formation. It is possible that there may have been a slight amount of differential movement between the beds of the formation due to the gentle folding, and this may account for a small part of the mica seen in bedding planes, but, as already noted, it is believed that a greater part of this mica is clastic. If there has been much movement it is probable that there would have been a greater development of secondary mica in continuous layers.

THICKNESS.

Because of the few exposures and the difficulty of ascertaining the variability of the dip, it is difficult to give an estimate of the thickness of the formation. Assuming an average southward dip of 8 degrees, and the average width of the quartzite belt to be 1,500 feet, the thickness of the formation may be little over 200 feet. But in some places the surface width is nearly 3,000 feet, and in other places the formation is cut out entirely. Moreover, the dip varies from 5 to 15 degrees. The thickness, therefore, while perhaps averaging about 200 feet, may vary between 500 feet and 0. E. J. Longyear in one place (1,025 paces north and 665 paces west of the southeast corner of sec. 35, T. 58 N., R. 21 W.) has drilled from the iron formation completely through the quartzite and found it to have a thickness of 69 feet.

RELATIONS TO OTHER FORMATIONS.

The Pokegama quartzite, forming as it does the base of the Upper Huronian series, rests unconformably upon the Lower Huronian and Archean series. This unconformity is considered under the heading "Relations of the Upper Huronian series to other series" (see pp. 180–181). The Pokegama quartzite is overlain by the iron formation, and while the two formations are essentially conformable in bedding and structure, there is between the two a thin but persistent layer of conglomerate, indicating a minor erosion interval. This is described in connection with the iron-bearing formation (see p. 154).

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SECTION II. THE BIWABIK FORMATION (IRON-BEARING).

DISTRIBUTION.

The Biwabik formation extends along the slopes of the range for its entire length, from west of Grand Rapids to Birch Lake, a distance of nearly 100 miles. The width of the formation, averages perhaps 1¼ miles, but is in places as great as 3 miles and in others as small as a quarter of a mile. The total area is approximately 127 square miles. The bounding formation on the north is, for the most part, the Pokegama quartzite, but where this is lacking the Biwabik formation comes in contact with the Lower Huronian and Archean rocks. To the south the iron-bearing formation is bounded by the Virginia slate, except in range 12 and a part of range 13, at the east end of the range, where the Duluth gabbro laps up over the formation.

On account of the covering of glacial drift, exposures of the iron-bearing formation, except in the eastern end of the district, are few. But the formation has been reached and pierced in thousands of places by drills and mining excavations, and it is therefore possible, particularly along the part of the range at present productive, to delimit the iron formation with a fair degree of accuracy. In parts of the district where explorations and mining have not been so extensive, especially in the west end of the district, future explorations are likely to show that the boundaries, particularly the southern boundary, are in some localities not correct.

The iron formation in general occupies the middle slopes of the Giants range, and its north and south boundaries have fairly uniform altitudes for considerable distances. By an examination of the map, however, it may be seen that the elevation of the iron formation increases from the west end of the district to the east, the total difference amounting to as much as 500 feet. This corresponds with the increased elevation of the range as a whole in this direction, although the higher elevation of the southern limit of the iron formation at the east end of the range is in part due to the fact that the lower parts of the formation are overlapped by gabbro. It may be further seen that the elevations of the north and south boundaries show local fluctuations as great as 200 feet, due to the folding of the formation and to differences in depth of erosion.

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KINDS OF ROCKS.

The great bulk of the Biwabik formation is *ferruginous chert*[a] more or less amphibolitic, calcareous, or sideritic and gray, red, yellow, brown, or green, with bands and shots of iron ore. It is analogous to the jaspers of the other iron ranges but differs in certain particulars, as will be seen on a subsequent page.

Associated with the chert, mainly in the middle horizon, are the *iron ores*. Their surface area is only about 5 per cent of the total area of the iron-bearing formation, and the proportion of their bulk to that of the iron-bearing formation is much less. Near the bottom of the Biwabik formation is a small amount of *conglomerate* and *quartzite*—that is, coarsely clastic sediments. A minute conglomeratic layer has also been observed in the Mahoning mine, in about a central horizon of the formation. In thin layers and zones throughout the iron-bearing formation, and particularly in its upper horizons, are layers of *slate* and of *paint rock*, the paint rock usually resulting from the alteration of the slate. Between the slate and the paint rock and the ferruginous chert are numerous gradational varieties, most of which come under the head of *ferruginous slate*. Associated with the slaty layers in the iron formation, or closely adjacent to the overlying Virginia slate, are green rocks made up of small green granules of ferrous silicate which are here called *greenalite*. It will be shown later that these are the original rocks from which most of the other phases of the iron formation, including the ores, have resulted by alteration. Finally, certain *calcareous and sideritic rocks* are present in small quantity, particularly near the upper horizons, associated with the greenalite rocks. The rocks of the iron formation are described below, beginning with the original type, the greenalite rock. The ores are reserved for a separate chapter.

GREENALITE ROCKS.

In limited quantity either just below the Virginia slate, or associated with some slate layer in the iron formation, are dull, dark-green rocks of rather uniform fine grain and with conchoidal fracture. Layers of slate, iron

[a] This rock has been called *taconite* by the geologists of the Minnesota survey, and the name has been much used locally. The term is not here retained for the reason that the rock is not different from ferruginous cherts of other parts of the Lake Superior region, as described in the monographs of the United States Geological Survey, and there is no reason to complicate rock nomenclature by adding a new name. There is no objection, however, to its local use.

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ore, and other phases of the iron formation usually mark their bedding. (See fig. *B*, Pl. VIII.) On close examination, and particularly when the surface is wet, there may be observed numerous ellipsoidal granules of a green substance of a very slightly lighter green than the matrix in which they lie. They are so small and of a color so nearly like that of the matrix that they are likely to be overlooked unless especially searched for. (See fig. *A*, Pl. VIII.) An occasional one is of much greater size than the average and looks like a conglomerate pebble in the rock.

Under the microscope the granules are conspicuous. Their cross sections are round, oval, in some cases with much elongation, crescent shaped, lense shaped, gourd shaped, or even sharply angular (Pls. IX, XIII, XIV, and XV). Here and there a curved "tail" seems to connect one granule with its neighbor (Pl. IX). Where in contact with a layer of iron carbonate or calcium carbonate, as they frequently are, the granules become more irregular in shape and project into or are included in the carbonate layers as irregular filaments and fragments. The carbonate is largely secondary and clearly replaces the granules, but some of it is perhaps original, and in this case the variation in shape of the granules where associated with the carbonate layers has a bearing on the origin of the ores, which is discussed on another page. One hundred and twenty measurements of the granules show an average greater diameter of 0.45 mm. and average least diameter of 0.21 mm., with average ratio of greatest to least of 100 to 47. The diameters rarely reach 1 mm. and seldom drop below 0.1 mm. Occasionally certain of the granules may be seen to be aggregated into larger granules, with well-rounded outlines, making the conglomerate-like fragments above mentioned. The greater diameters of the granules, for the most part, are parallel to the bedding, and in fact this arrangement largely determines the bedding. In ordinary light the granules are green, greenish yellow, brown, or black. The green and yellow ones are transparent, while the brown and black are nearly or quite opaque. Under crossed nicols the granules are either entirely dark or show a very faint lightening, hardly sufficient to disclose a color. Here and there incipient alterations to chert, grünerite, cummingtonite, or actinolite, scarcely discernible in ordinary light, give low polarization colors in minute spots and make the term aggregate polarization applicable. In reflected light the transparent green and yellow granules appear black or

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PLATE VIII.

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PLATE VIII.

GREENALITE ROCK.

FIG. *A*.—Greenalite rock. Specimen 45647. From near Duluth, Missabe and Northern Railway track, 1 mile south of Virginia. Granules of greenalite, but little altered, stand in a matrix of chert. Described pp. 101–115.

FIG. *A'*.—Portion of surface of specimen shown in *A* slightly magnified to show greenalite granules to better advantage.

FIG. *B*.—Interbanded greenalite and slate rock. Specimen 45176. From 100 paces north 500 paces west of SE. corner of sec. 22, T. 59 N., R. 15 W. Natural size. The black portion of the rock is slate and the green portion is made up of greenalite granules lying in a matrix of chert. Greenalite is characteristically associated with slaty layers in the iron formation; indeed, it is due to their protection that greenalite has been retained in comparatively unaltered form. Described pp. 101–115.

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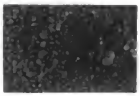

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PLATE IX.

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PLATE IX.

PHOTOMICROGRAPHS OF GREENALITE GRANULES.

FIG. *A*.—Greenalite rock. Specimen 45478, slide 15052. From 160 paces north 500 paces west of the southeast corner of sec. 22, T. 59 N., R. 15 W. Without analyzer, x 50. The slide is selected to show both the fresh and slightly altered granules. Note the peculiar greenish-yellow color of the granules, their irregular shape, and their curving tails, which seem in some cases to connect with adjacent granules. The homogeneous greenish-yellow colors represent the unaltered parts. The bright-green and dark-green colors represent grunerite which has been developed from the alteration of the greenalite. The dark green is perhaps in small part iron oxide. Described pp. 101–115.

FIG. *B*.—The same with analyzer, x 50. The unaltered portions of the granules are nearly or quite dark under crossed nicols. Where the granules have altered to grünerite the polarization colors appear. The matrix consists of fine-grained chert in which the individual particles are very irregular in shape and size. Illustrated pp. 101–115.

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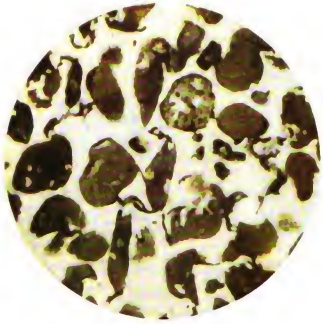

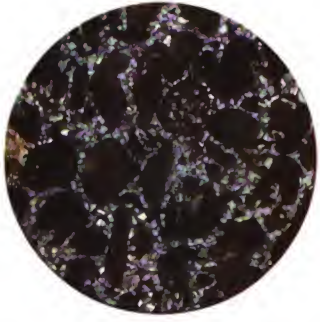

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dark green or dark yellow, while the opaque brown and black granules exhibit a rough light-green surface. Were it not for the light-green surface in reflected light certain of the opaque dark-brown granules would be mistaken for iron oxide in ordinary and polarized light.

The matrix of the rocks containing the unaltered green granules varies widely in amount, from a mere interstitial filling to an abundant mass in which the granules are widely separated. The matrix may be almost pure chert; it may be nonaluminous, monoclinic amphibole, actinolite, grünerite, or cummingtonite; it may be largely iron or calcium carbonate, although where the carbonate is abundant the granules are usually sparse and irregular; it may consist of any combination of chert, amphibole, and carbonate, with a small amount of accessory iron oxide.

Originally the matrix may have had a somewhat different character. In the rocks containing the least altered granules the matrix is predominantly chert and subordinately light-colored amphiboles and carbonate. As the rocks become altered they contain more iron oxide and dark amphiboles, which will be shown on a subsequent page to develop from the alteration of the granules. The lighter amphiboles are themselves known to be a secondary development from chert and carbonate rocks. It seems likely, therefore, that the original matrix of the green granules was largely chert and in small part carbonate. In the freshest rocks now found the chert is much recrystallized and the original carbonate is largely leached out or replaced by actinolite.

The specific gravity of the unaltered granules can not be satisfactorily determined, because of the practical impossibility of separating the granules from the matrix. Determinations of the specific gravity of the rock as a whole give results ranging from 2.7 to 3. As the matrix is largely quartz in the form of chert, which is known to have a specific gravity in the neighborhood of 2.65, the figures above given for the unaltered rock are too low for the granules themselves, although their incipient alterations to iron oxide and amphiboles tend to raise the specific gravity. So far as the matrix is colorless amphibole, it is apparent that the specific gravity of the green granules is lower than the figures obtained for the rock, for the specific gravity of the colorless amphiboles is above 3. One exceptionally fresh specimen in which the granules lie in a matrix of chert gave a result of 2.7. The matrix in this case makes up something more than half of the

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rock mass, and it therefore seems probable that the true specific gravity of the granules is a little above 2.75.

Four analyses of rocks containing the least altered granules observed have been made by Mr. George Steiger of the United States Geological Survey. He found that by treatment with hot concentrated hydrochloric acid most of the granules and their associated alteration products dissolved out, leaving a residue of almost clear silica, which probably mainly represents the matrix.

Analyses of greenalite rocks.

	1.		2.		3.		4.
	Sol.	Insol.	Sol.	Insol.	Sol.	Insol.	
SiO_2	13.45	48.45	[a]19.30	36.50	33.11	13.01	[b]50.96
Al_2O_3	.37		.61		.56		1.09
Fe_2O_3	15.00	.64	13.83	.76	6.44	2.60	5.01
FeO	10.28		17.57		30.93		30.37
MgO	2.33	.....	3.22	.....	5.35	.....	5.26
CaO	.28	.....	None.	.....	None.	.....	.04
Na_2O	None.	.....	None.	.....	None.	.....	None.
K_2O	None.	.....	None.	.....	None.	.....	None.
H_2O-	2.50	.....	2.38	.....	1.34	.....	.75
H_2O+	4.17	.....	5.74	.....	6.13	.....	6.41
TiO_2	None.	.....	None.	.....	None.	.....	None.
CO_2	2.04	.....	None.	.....	None.	.....	None.
P_2O_5	None.	.....	None.	.....	None.	.....	None.
S	.....	.....	.....	.....	.....	.....	Trace.
MnO	.....	.....	.....	.....	.....	.....	None.
BaO	.....	.....	.....	.....	.....	.....	None.
Carbon in organic matter	.....	.....	.....	.....	.....	.....	.21
Undetermined	.....	.52	.....	.15	.....	.38	.....
	50.42	49.61	62.65	37.41	83.86	15.19	100.10
	49.61	.....	37.41	.....	15.99	.....	.....
	100.03	.....	100.06	.....	99.85	.....	.....

[a] Of which 3.3 was found in the rock upon treatment with HCl, probably opal.
[b] Of which 23.96 is soluble.

1. Specimen 45758. From 250 paces west, 83 paces north, of the west quarter post, sec. 35, T. 59 N., R. 15 W. The finely ground rock was evaporated on the water bath to dryness, with 50 cc. of 1–1 HCl, taken up with water slightly acidified with HCl, and filtered. Soluble silica was then determined in this residue by boiling with 5 per cent solution of Na_2CO_3. A determination of soluble SiO_2 was then made in the rock before treatment with HCl and subtracted from the first soluble SiO_2 found, which gave the figure for SiO_2 in the soluble portion.

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2. Specimen 45765. From test pit in Cincinnati mine. The soluble portion was found by evaporating to dryness on the water bath with 50 cc. of 1–1 HCl, and taking up with water slightly acidified with HCl. The residue was then boiled fifteen minutes with a 5 per cent solution of Na_2CO_3 to dissolve any soluble silica, this silica determined and placed with the soluble portion. The residue was ignited and finally heated for fifteen minutes over the blast lamp, weighed, and then a rough analysis made, which is found in the second column. The small amount of iron shown in the insoluble portion could easily have been carried down mechanically. A determination of soluble silica was then made in the rock before treatment with HCl and found to be 3.3 per cent. Subtracting this from the total soluble silica 16 per cent of soluble silica remains for the part dissolved in HCl.

3. Specimen 45766. From test pit in Cincinnati mine. The finely ground rock was evaporated on the water bath to dryness, with 50 cc. of 1–1 HCl, taken up with water slightly acidified with HCl, and filtered. Soluble silica was then determined in this residue by boiling with 5 per cent solution of Na_2CO_3. A determination of soluble SiO_2 was then made in the rock before treatment with HCl and subtracted from the first soluble SiO_2 found, which gave the figure for SiO_2 in the soluble portion.

4. Specimen 45180. From 500 paces west, 100 paces north of the southeast corner of sec. 22, T. 59 N., R. 15 W. Owing to presence of organic matter the determination of ferrous iron is probably high.

The interpretation of these results requires separate discussion because of the variation in nature and amount of associated minerals.

1. Green and brown transparent granules, and opaque brown and black ones, containing small amounts of secondary chert, carbonate, and limonite, stand in a matrix of chert. One large pebble-like area consists of granular limonitic material with a small amount of carbonate. In this area the outlines of granules can be distinctly seen, and the limonite clearly results from alteration of the granules.

The undissolved portion probably mainly represents the matrix. The dissolved portion probably mainly represents the green granules, the limonite, and carbonate. In calculating the composition of the green granules, the carbon dioxide, with enough of the bases to satisfy its valence, may be eliminated. As the microscope does not show conclusively whether carbonate is calcite, dolomite, or siderite in the calculation, the bases may be supposed to be combined with carbon dioxide in proportion to their strength. Thus the calcium oxide present, 0.28 per cent, may be supposed to be combined with carbon dioxide, which would leave 1.82 per cent carbon dioxide available for combination with other bases. Magnesium oxide is next in strength, and 1.67 per cent would be required to combine with the remaining carbon dioxide. This would leave 0.66 per cent of magnesium oxide, which may be supposed to belong with the green granules or with the associated alteration products. It is possible that the carbon dioxide may be combined in part with ferrous iron, but in the absence of definite information the above combination is supposed to hold. Whatever

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the combination, it will be noted that the total amount of carbon dioxide is so small that the exact determination of the combination is not a matter of consequence. After making deductions for the carbonates, the composition of the green granules and the associated alteration products is as follows:

SiO_2	13.45
Al_2O_3	.37
Fe_2O_3	15.00
FeO	10.28
MgO	.66
H_2O above 110°	4.17

We know that iron protoxide and magnesium oxide never occur in rocks except in combined form. The magnesium compound known as brucite ($Mg(OH)_2$) has not been noted in these rocks. It is necessary to assume that sufficient soluble silica is combined with ferrous iron and magnesia to satisfy their valence, and when this amount is deducted little or none is left for combination with the ferric iron. It is thus clear that a large portion of the green granules is ferrous silicate. It is further clear that the ferric iron shown by the analyses is in the form of ferric oxide, and thus probably secondary. If original, it may still be independent of the green granules, and there remains only a possibility that the ferric oxide may be an original constituent of the green granules themselves. This is in accord with the microscopic observation of the presence of a considerable amount of limonite in the slide. The limonite is secondary and independent of the green granules, and thus the ferric iron, with the water combined with it, may be eliminated from the discussion of the composition of the green granules. Of the combined water shown in the analysis 2.53 per cent would be required for combination with the ferric iron, on the assumption that the latter is all in the form of limonite, thus leaving 1.64 per cent of water probably belonging with the green granules. It is concluded, therefore, that the material of the green granules is essentially a hydrated ferrous silicate, with a small amount of magnesium and possibly a slight amount of ferric oxide and alumina. The total absence of the alkalies and phosphorous is to be noted.

2. In this rock the granules are green and transparent and in part dark brown, black, and opaque, and show a very slight and practically negligible alteration to greenish and colorless amphibole. The matrix is chert. The undissolved portion probably mainly represents the matrix. The dissolved portion mainly represents the green granules.

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The composition of the green granules, together with their minute alteration products, is therefore as follows:

SiO_2	16.00
Al_2O_3	.61
Fe_2O_3	13.83
FeO	17.57
MgO	3.22
H_2O above 110°	5.74

Arguing as above, we know that iron protoxide and magnesium oxide never occur in rocks except in combined form. The magnesium compound known as brucite ($Mg(OH)_2$) has not been noted in these rocks. It is necessary to assume that sufficient soluble silica is combined with ferrous iron and magnesium oxide to satisfy their valence, and when this amount is deducted little or none is left for combination with the ferric iron. From this it is clear that a large portion of the green granules is ferrous silicate. It is further clear that the ferric iron shown by the analyses is in the form of ferric oxide, and thus probably secondary. If original it may still be independent of the green granules, and there remains only a possibility that the ferric oxide may be an original constituent of the green granules themselves, but as no iron oxide can be certainly observed in the slide this possibility must be recognized. Thus most of the ferric oxide, together with any water which may be combined with it, may be eliminated from the discussion of the composition of the green granules. If the iron oxide were all limonite it would not require all the combined water, and thus a considerable portion of the combined water must belong with the green granules. Thus the material of the green granules appears to be mainly hydrated ferrous silicate with a small amount of magnesium and perhaps also small portions of ferric oxide and alumina The entire absence of the alkalies and phosphorus is to be noted.

3. The granules, of a greenish-yellow color, are slightly altered to colorless and in part slightly greenish amphibole, and lie in a matrix of colorless and slightly greenish amphibole, associated with a subordinate amount of chert. There is present in addition a small amount of oxide of iron which may be either more or less hydrated hematite or magnetite. The insoluble portion, which is small in amount, is shown by the analysis to be mainly silica, with a subordinate amount of ferric iron. The soluble portion contains the greenish granules, the amphiboles, and the major portion of the iron oxide As there is microscopic evidence both in this

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rock and in the iron-formation rocks as a whole that the amphiboles result from the alteration of the green granules, and in many cases at least merely by recrystallization and dehydration of the substance of the green granules, it is apparent that no great error will be introduced if the substance of the amphiboles be considered together with the rest of the soluble material in determining the approximate composition of the green granules. The composition of the green granules, together with amphiboles resulting from their alteration, and the black iron oxide, is:

SiO_2	33.11
Al_2O_3	.56
Fe_2O_3	6.44
FeO	30.93
MgO	5.35
H_2O above 110°	6.13

The percentage of ferric oxide shown is small, and it is thought that it is largely accounted for by the oxide seen in the slide and thus ought not to be counted as belonging with the green granules. If a portion of the iron is magnetite, then a small percentage of ferrous iron belongs to it. If it were all magnetite, about 3 per cent of the ferrous iron would be so combined, and hence the true figure is probably less than this. At most but a very small percentage of the combined water can be supposed to belong with the ferric oxide, and also but little can belong with the amphiboles; the large percentage of combined water shown by the analyses belongs largely to the substance of the green granules. The analysis therefore shows the original green material to be essentially a hydrous ferrous silicate with a considerable percentage of magnesium, and perhaps small amounts of ferric oxide and alumina. The entire absence of the alkalies and phosphorus is to be noted.

4. The granules are in part yellowish brown and transparent, and in part dark brown, black, and opaque, the latter showing the characteristic rough, green surface in reflected light. They are largely fresh, but a number of them show slight alterations to colorless, light-brown, and light-green amphibole. There is present also a small amount of black iron oxide. The matrix is mainly a felted mass of colorless amphibole, with a slightly greenish pleochroism, with high double refraction and low angle of extinction, which corresponds in its properties to actinolite. The amphibole within and adjacent to some of the granules may be seen in all stages of

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development through the alteration of the granules, and it is probable that all of the amphibole has developed in this way.

In this analysis the composition of the entire rock was first determined and then the soluble silica found. No determination was made of the substance left in the residuum after the treatment with hydrochloric acid, and it is not possible to state how the amphibole in the matrix acted under the treatment. The analysis, therefore, affords no direct evidence of the composition of the green granules. But it seems probable that at least a part of the amphibole went into solution with the hydrochloric-acid treatment. The soluble portion would, then, contain the original green material, an unknown quantity of amphibole, and a slight amount of black oxide of iron. If the amphibole which may have gone into solution be considered as an alteration of the original green material essentially by simple recrystallization, as it certainly is in the iron formation as a whole, then its ingredients need not be separately considered in arriving at an approximation of the composition of the original green material. Most of the ferric iron shown in the analysis is accounted for by the black oxide of iron seen in the slide. As the black oxide of iron is at least partly magnetite a small percentage of ferrous iron must be supposed to belong with it. If the ferric oxide all belongs to magnetite, 2.2 per cent would be so required; so the true figure is probably something less than this. A still further deduction must be made from the ferrous iron, as the analyst makes the statement that the percentage of ferrous iron is probably high because of the presence of organic matter. Only a very small percentage of the combined water can be accounted for by combination with the oxide of iron, for this is in small quantity, and, moreover, largely magnetite. Neither can any of the water be supposed to belong with the amphiboles, for the latter are nearly anhydrous. Thus most of the water belongs with the substance of the green granules. It is clear that at least a part of the material of the dissolved portion is a hydrous ferrous silicate, and it is certain that this part belongs with the unaltered green granules.

Assembling the above results, it appears that the ferric iron occurs in the rock mainly as sesquioxide, for the soluble silica is accounted for by the ferrous iron and magnesia present, leaving none for the ferric iron; that in three slides of the four of the rocks analyzed the ferric oxide may be observed to be present and to be probably secondary; and, hence, that

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the iron oxide shown by the analyses is mainly secondary and not to be considered as belonging with the substance of the unaltered granules. It appears further that the alumina and lime are in such small quantity as to be practically negligible. It appears still further that there is far more than enough combined water to combine with the ferric iron to form ferric hydrate, and thus that a considerable portion of combined water shown by the analyses may be taken to belong to the green granules. Finally, it appears that the substances which can not be accounted for in any other way and which clearly belong with the green granules are silica, ferrous iron, magnesium oxide in small proportions, and water. It is therefore concluded that the substance of the green granules is essentially a hydrous ferrous silicate with a subordinate amount of magnesium, and that if ferric iron is present at all as an original constituent of the green granules it is in small quantity.

This conclusion is essentially in accord with that reached by Dr. J. E. Spurr in his report on the Mesabi district published in 1894.[a]

Having concluded the substance of the green granules to be mainly silica, ferrous iron, magnesium oxide, and water, we may ascertain whether or not there is any uniformity in the proportions of these elements. The ratios of the silica, ferrous iron, and magnesium in the four analyses, calculated on the basis of 100, appear in the subjoined table. The percentage of water is not included for the obvious reason that, while it is certain that much of it belongs with the granules, no quantitative estimate can be made of its amount because of the uncertainty as to the portion which belongs with the ferric hydrate.

	1.	2.	3.	4.	Average.
SiO_2	55.1	43.7	47.7	40.2	46.8
FeO	42.1	47.5	44.6	50.9	46.3
MgO	2.8	8.8	7.8	8.9	7.1

The relative proportion of the ferrous iron and silica above shown suggests a combination of the two on the basis of one molecule of each. Theoretically the percentages of the two in such a combination would be—

Silica	45.62
Ferrous iron	54.38

[a] Geol. Nat. Hist. Survey Minnesota, Bull. No. 10.

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The average of the ferrous iron, 46.3, is about 8 per cent less than the theoretical percentage. The magnesium oxide, which has a higher combining power than the iron, more than makes up for this deficiency.

On a subsequent page (pp. 141–143) is given an analysis of a rock in which the green granules have been altered to a dark-green and brown amphibole, probably grünerite, apparently through simple recrystallization and dehydration. The alteration has occurred under deep-seated conditions, and it is probable that little, if any, addition or subtraction of material has taken place, other than that involved in dehydration.[a] The composition of the amphibole ought to give a clew to the composition of the original green substance. It is there found that the principal constituents of the amphibole are silica and ferrous iron, in the following proportions:

SiO_2	47.5
FeO	52.5

The correspondence of these percentages with those above given is evident.

It is apparent that the above results are not sufficiently accordant to show that the substance under discussion has a definite and uniform composition. On the other hand, the impurities and alterations cause such variations that it can not be said that the green granules do not have definite chemical composition. If the granules do have a definite composition, the above results indicate the most probable formula to be $Fe(Mg)OSiO_2nH_2O$.

Dr. Spurr, after his study of the green granules, concluded to call them "glauconite." In view of the fact that potash is insisted upon as one of the essential constituents of glauconite by most mineralogists (see pp. 239–243), the entire absence of potash in the substance under discussion is taken to preclude the application of the term glauconite. The substance apparently corresponds to no known mineral species. As it will be necessary and convenient to have a term by which to refer to it in the present discussion, the name "greenalite" is coined for use in this report.

The origin of greenalite and the details of the similarities and differences between greenalite granules and granules of glauconite, concretions of iron oxide and chert, and other granule and concretionary structures, are discussed in Chapter IX, on the origin of the iron ores.

[a] In a monograph on Metamorphism (in press) C. R. Van Hise emphasizes the fact that alterations in the deep-seated "zone of anamorphism" for the most part involve no considerable transfers of material.

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FERRUGINOUS, AMPHIBOLITIC, SIDERITIC, AND CALCAREOUS CHERTS.

The following description applies to the normal types of chert occurring through the central and western portions of the range. The highly metamorphosed chert characteristic of the east end of the range is given a separate description on a subsequent page.

The cherts are gray, yellow, red, brown, or green rocks, with irregular bands and shots and granules of iron oxide, varying in quantity from predominance almost to disappearance (Pl. X–XII). A slight brecciation thoroughly recemented may be occasionally observed, and a pitted surface, due to the solution of certain of the constituents, is not uncommon. The iron oxide is mainly intermediate between hematite and limonite, and to a subordinate extent is magnetite, and its color accordingly ranges from red to yellow or to black. The variety of colors of the chert and the iron oxide, their irregular association, and their variation in relative abundance give the cherts most highly varied aspects; yet no phase of the cherts is likely to be mistaken for any other rock by anyone reasonably familiar with the iron-formation rocks of the Lake Superior region. To the casual observer, the massive, lighter-colored cherts, containing little iron oxide, resemble quartzite, and, indeed, have been frequently so called. However, the splintery fracture of the chert and the absolute lack of rounded clastic grains, aside from the usual content of iron oxide in layers or spots or minute grains, are unfailing criteria for the discrimination of the two. The ferruginous cherts differ from the jaspers or jaspilites of the old ranges of Lake Superior in lacking their even banding and brilliant red color as well as the microscopic features described below.

When studied under the microscope, it is apparent that all the rocks here described as chert are genetically connected. In looking over 250 slides but few have been observed which do not show some evidence of the derivation of the rock from the greenalite rocks above described. The granule shapes are still largely preserved,[a] but the alterations have tended in some cases to make the shapes more irregular and to partly or wholly obliterate them. The alteration of the granules has been almost entirely metasomatic, for there is little evidence of dynamic movement resulting in the breaking up of the constituents of the rock.

[a] Sparr has applied to this texture the term "spotted granular." Geol. Nat. Hist. Survey Minnesota, Bull. No. 10.

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The greenalite has been replaced by cherty quartz, magnetite, hematite, limonite, siderite, calcite, grünerite, cummingtonite, actinolite, epidote-zoisite, or any combination of them. The extent and nature of the alteration replacement vary within wide limits. The granule may be mainly greenalite, showing incipient crystallization of quartz, grünerite, or actinolite, visible only under crossed nicols. The granules may be represented almost wholly by hematite, limonite, magnetite, intermediate varieties, or any combination of them. The oxides may be arranged irregularly or concentrically. In the iron ores the granules are entirely represented by iron oxide, although their shapes are in part obliterated. The granule may be represented almost wholly by chert, which may be distinguished from that of the matrix by its coarser or finer texture, or, if not by texture, by distribution of pigment. In ordinary light chert granules may be marked by the pigments which in parallel polarized light are completely obscured by the crystallization of the chert (Pl. XV, figs. *C* and *D*), or the granules may not be seen in ordinary light and be conspicuous under crossed nicols because of the crystallization (specimen 45191). Or the crystallization of the chert may have entirely obliterated the granules for much of the slide, both in ordinary and polarized light. The granules may be represented entirely by green, yellow, and brown grünerite, cummingtonite, or, perhaps, actinolite, or all (specimen 45497), which in ordinary light may be scarcely distinguishable from the unaltered greenalite granules, but which become apparent under crossed nicols by their double refraction. The granule may be represented by calcite or siderite in rhombs or irregular grains, sometimes showing zonal growth, which, for the most part, are clearly replacements of the granules (specimens 45171, 45172, 45174, 45219, 45222). Most commonly the granules are represented by a combination of any or all of the minerals above named. Of these combinations, that of chert and iron oxide stands first. The two substances occur in all proportions with a great variety of arrangement. The two may be irregularly intermingled, or the iron oxide may form a rim about a cherty interior, or, though not frequently, the chert and iron oxide may be in concentric layers in the manner of normal concretions, or polygonal areas of fine chert may contain spots of iron oxide in the center of each, as well as a rim of iron about their peripheries (Pl. XIV, figs. *A* and *B*), suggesting an organic structure. The alteration and

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replacement of the greenalite and the conditions favoring the development of the different minerals are discussed under the origin of the ores.

In addition to the derivatives of the greenalite granules there are present a few concentric concretions of iron oxide and chert about quartz (see Pl. XIII, fig. *D*), which may have been secondarily developed from some substance other than the greenalite. These are similar to concretions in the Penokee-Gogebic iron-bearing formation,[a] where they have developed from the alteration of an iron carbonate. (See Pl. XVI, fig. *A*.) The secondary concretions in the Mesabi district may also be developments from iron carbonates, which are now associated with unaltered portions of the formation and probably existed formerly in the portions which are at present altered. The secondary concretions are different from the greenalite granules in their beautifully developed concentric structure, as may be noted by a comparison of the figures of Pl. XIII. While a few of the granules themselves have a concentric structure resulting from zonal alteration, this is usually poorly developed and there is ordinarily little difficulty in distinguishing it from that of the secondary concretion, though in some cases it is possible that some of the supposed secondary concretions formed from carbonate may be really secondary alterations of original granules.

Spherulites of epidote, rarely to be observed, while in part replacements of the granules, are also clearly secondary developments in the matrix.

The occurrence of true secondary concretions associated with the derivatives of greenalite granules in the Mesabi district suggests that greenalite granules may be present with the secondary concretions in the Gogebic district. With this idea in mind a number of specimens and slides from the Penokee district have been examined and the descriptions given by Van Hise in Monograph XIX carefully read. While a great majority of the granule structures in the Gogebic rocks are unquestionably secondary concretions resulting from the alteration of iron carbonate, as shown by Van Hise, a considerable number of granules were found which are almost certainly derived from greenalite granules (see fig. *B* of Pl. XVI), for they are identical in every way with the derivatives of the greenalite granules in the Mesabi district.

In this connection it is of interest also to note that H. L. Smyth found

[a] Described and figured by C. R. Van Hise in Mon. U. S. Geol. Survey Vol. XIX, 1892.

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round and oval forms in the ferruginous cherts of the Groveland formation (Lower Huronian) of the Felch Mountain area in Michigan, which, on comparing with the greenalite granules and their derivatives from the Mesabi district, he concluded had the same origin.[a]

The matrix of the chert may be a sparse interstitial filling between the granules, or it may form most of the rock mass and contain but few isolated granules. The matrix is similar to that of the unaltered greenalite rocks in that it is mainly chert, but it differs in containing far more actinolite, grünerite, cummingtonite, iron oxide, calcite, and siderite, and rarely epidote-zoisite in spherulitic form. Sometimes also green chloritic substances are abundant, either irregularly distributed through the matrix or forming a definite rim about the granule. In the latter case the chlorite is in part in the fibrous form known as delessite (specimen 45173) and much resembles uralite. The recrystallization of the rock has in some cases made the chert in the matrix coarser than that of the granules and in some cases the reverse. The leaching out of the carbonates and greenalite from the matrix has occasionally left cavities which give the pitted character to the weathered surface of the cherts.

Accompanying the recrystallization of the chert has been its frequent adoption of radial or sheaf-like forms, giving black crosses under crossed nicols. These sheaves, as well as the sheaves of actinolite, grünerite, and cummingtonite, and rarely epidote, frequently lie with their butts against the outlines of the granules and send their points outward until they interlock with similar projections from adjacent granules. Commonly, also, one or more of the constituents of the matrix may be observed to lie partly in the matrix and partly in the granule, thus helping to obliterate the granule. Indeed, under crossed nicols the granules may not be observed, while in ordinary light their position may be indicated by the distribution of the fine pigment. (See figs. *C* and *D* of Pl. XV.)

All of the constituents in the matrix are secondary except, perhaps, a part of the chert, and even this has been thoroughly recrystallized. The amphiboles and iron oxide may be observed to have developed by the alteration of the granules and some of the lighter amphiboles by the alteration of carbonate and chert in the matrix. The carbonate is largely, though not entirely, replacement from without, for it may be observed

[a] Mon. U. S. Geol. Survey Vol. XXXVI, 1899, pp. 421–422.

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replacing nearly all the other constituents of the rock and to occur in minute veins crossing the rock.

The segregation of the iron oxide in the granules and matrix due to the alteration of the greenalite, when on a large scale, has yielded the iron-ore deposits, and this feature of the alteration will be more fully discussed in connection with the origin of the ores.

The above description covers the general characteristic features of the greater part of the cherts of the iron formation. There remain certain minor and peculiar phases of the cherts which merit further brief description.

Characteristic of basal horizons of the iron formation is an exceedingly dense siliceous and ferruginous rock, with gnarled and contorted interbandings of red, white, brown, and black layers. Some of the quartz is vein quartz which fills partings essentially parallel to the layers. (See fig. *A* of Pl. XII.) The rock in general has the hard vitreous aspect of jasper of the old iron ranges of Lake Superior, but the bands are not nearly so clear cut and even as in typical jasper. Under the microscope the rock is seen to be an exceedingly fine-grained chert containing the usual granules, which are here of approximately the same composition as the groundmass, but marked off by iron oxide in evenly distributed particles or in concentric rings. The characteristic feature of the rock is the matrix, which contains particles of iron oxide and of greenish and yellow chloritic and ferrous silicate substances, and occasional axiolites of chalcedonic quartz, in parallel gnarled and contorted lines resembling the flowage lines in the matrix of a vitreous lava. (See fig *B* of Pl. XIII.)

The rock in places grades into a breccia, and is with exceeding difficulty distinguished from certain phases of true conglomerates containing jaspery fragments at the base of the iron formation. Indeed, the similarity is so great as to suggest that possibly some of the rocks which have been described as conglomerates are really breccias. However, most of the conglomerates have true waterworn quartzitic matrix, which may be easily distinguished from the cherty matrix of the brecciated rocks.

The presence of the breccia at the basal horizon of the chert leads one to suspect that the gnarled and contorted nature of the ferruginous chert at this horizon is due to differential movement between the ferruginous chert and the quartzite during the folding of the Upper Huronian series. (See pp 178–180.) Spurr has described the brecciation of the ferruginous

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PLATE X.

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PLATE X.

FERRUGINOUS CHERT OF IRON-BEARING FORMATION.

FIG. *A*.—Gray ferruginous chert. Specimen 45027. From Chicago mine in sec. 4, T. 58 N., R. 16 W. Natural size. This is one of the characteristic aspects of the ferruginous cherts of the iron formation. Under the microscope iron oxide and chert can be seen still marking the shapes of the greenalite granules. Described pp. 116–120.

FIG. *B*.—Ferruginous chert. Specimen 45588. From the Mahoning mine. Natural size. The rock shows interbanding of chert with iron oxide. Described pp. 116–120.

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PLATE XI.

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PLATE XI.

FERRUGINOUS CHERT OF IRON-BEARING FORMATION.

FIG. *A*.—Ferruginous chert. Specimen 45035. From Mountain Iron mine. Natural size. This rock is a dense yellow chert which is frequently associated with iron-ore deposits. Under the microscope the greenalite granules are seen to be represented by slightly polarizing fine-grained chert, which lies in a matrix of limonite. Described pp. 137–138.

FIG. *B*.—Ferruginous chert. Specimen 45309. From Diamond mine in sec. 15, T. 56 N., R. 24 W. Natural size. The rock shows the irregular mottling of the iron oxide. The remains of the greenalite granules can be seen under the microscope. Described pp. 116–120.

FIG. *C*.—Ferruginous chert. Specimen 45003. From Clark mine. Natural size. The rock shows interbanding of chert with iron oxide. Described pp. 116–120.

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(A)

(B)

(C)

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PLATE XII.

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PLATE XII.

FERRUGINOUS CHERT, "JASPERY" PHASE, AND FERRUGINOUS CHERT IN CONTACT WITH QUARTZITE OF IRON-BEARING FORMATION.

FIG. *A*.—Ferruginous chert with gnarled and contorted banding. Specimen 45420. From drift fragments just east of Mesaba station in sec. 21, T. 59 N., R. 14 W. Natural size. This phase of ferruginous chert is characteristic of the basal horizon of the Biwabik formation. The red bands are iron-stained chert; the lighter ones are chert and vein quartz. Under the microscope the shapes of the granules can be seen to have been retained by chert and iron oxide. Described p. 120.

FIG. *B*.—Ferruginous chert in contact with quartzite of iron formation. Specimen 40652. From the Cincinnati mine. Natural size. The chert is the gnarled and contorted phase characteristic of basic horizons. The sharpness of its contact with the ferruginous quartzite is to be noted. In some places ferruginous quartzite and chert of this kind are minutely interbanded at this horizon. Described, pp. 120 and 156.

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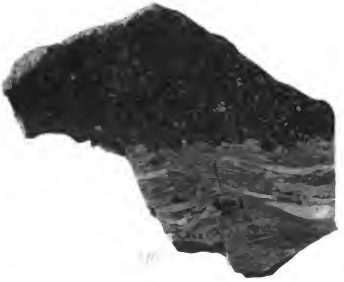

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PLATE XIII.

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PLATE XIII.

PHOTOMICROGRAPHS OF FRESH AND ALTERED GREENALITE GRANULES AND FERRUGINOUS CHERT CONCRETION.

FIG. *A*.—Greenalite rock with bands of carbonate. Specimen 45178, slide 15652. From 100 paces north, 500 paces west of southeast corner of sec. 22, T. 59 N., R. 15 W. Without analyzer, x 50. Greenallte granules slightly altered to grünerite, iron oxide, and chert, stand in a matrix of chert. On the left side of the figure is a band of carbonate, probably largely calcium carbonate, but perhaps in part iron carbonate. Attention is called to the irregular nature of the greenalite granules near the contact with the carbonate band. The irregular dark fragments in the carbonate band are also greenalite and their alteration product grünerite. Described pp. 101–115.

FIG. *B*.—Chert with granules and banding. Specimen 45419, slide 15706. From hill just east of town of Mesaba. Without analyzer, x 50. This is a phase of chert which is typical of basal horizons of the iron formation. The rock consists essentially of chert. Iron oxide occurs outlining the altered granules, and also occurs in contorted lines and bands representing flow lines in a lava. Described p. 120.

FIG. *C*.—Greenalite granules. Specimen 45765, slide 16305. From Cincinnati mine. Without analyzer, x 40. The granules are for the most part unaltered, and are dark green, light green, or yellow. Some of them show alterations to iron oxide and to dark-green chloritic material. Where altered they become dark brown, black, or dark green. The matrix is entirely chert. Evidence of crushing is to be observed in minute cracks ramifying through the slide. Note the remarkable similarity in shapes of these granules to those of the green granules in Clinton ores, illustrated Pl. XXI.

FIG. *D*.—Concretionary chert. Specimen 40767, slide 15415. From the NE. ¼ of the SE. ¼ of sec. 35, T. 59 N., R. 17 W. With analyzer, x 100. This is one of the rare normal concretions in the iron formation of the Mesabi district. The interior is a single grain of quartz. This is surrounded by concentric layers of quartz and iron oxide, the latter somewhat hydrated. The matrix is chert. This structure resembles the concretions figured by Van Hise from the Gogebic district (see Pl. XVI), and is believed to be quite different from the greenallte granules figured in the preceding plates. Described p. 118.

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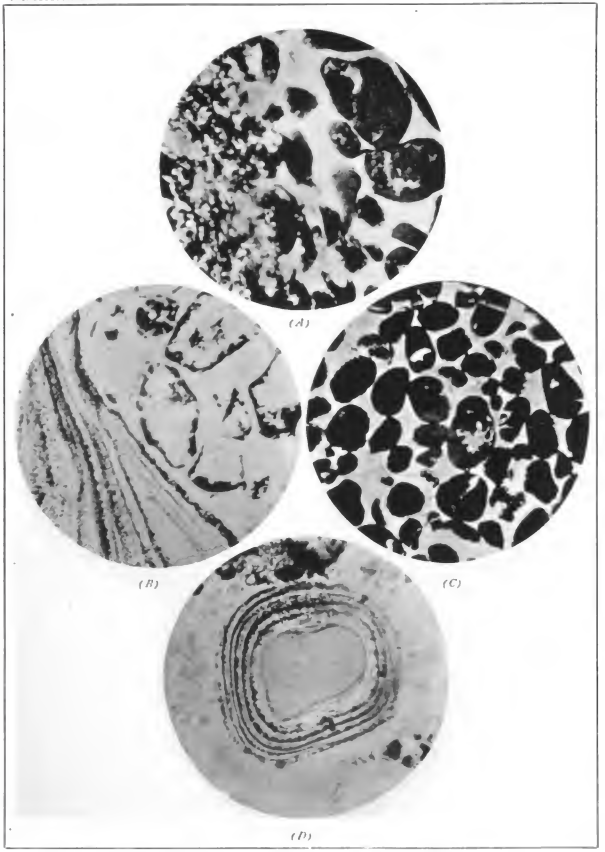

PHOTOMICROGRAPHS OF FRESH AND ALTERED GREENALITE GRANULES AND OF FERRUGINOUS CHERT CONCRETION.

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PLATE XIV.

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PLATE XIV.

PHOTOMICROGRAPHS OF FERRUGINOUS CHERT GRANULES, SHOWING MOTTLING.

FIG. *A*.—Ferruginous chert with mottled granule. Specimen 45628, slide 15978. From near the center of the SW. ¼ of sec. 10, T. 58 N., R. 19 W. Without analyzer, x 125. The granule here shown is composed of chert and reddish iron oxide. The chert occurs in small polygonal blocks separated by the oxide. Each of the chert individuals contains in its interior a more or less noticeable nucleus of iron oxide. The matrix is chert. A similar structure has been noted in the iron ores of the Vermilion district and in the Clinton ores. In the latter cases the mottled structure is clearly due to the replacement of a shell with regular structure. Described p. 117.

FIG. *B*.—Another granule in the same slide, showing a different aspect of the same feature. Described p. 117.

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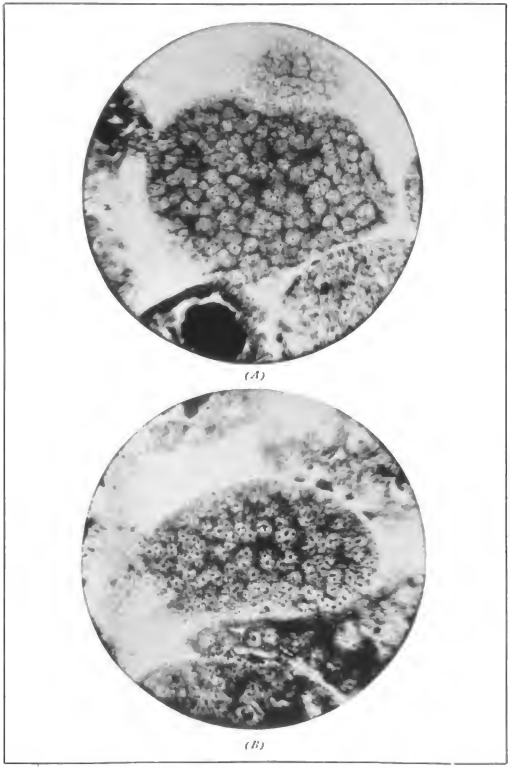

(A)

(B)

PHOTOMICROGRAPHS OF FERRUGINOUS CHERT GRANULES SHOWING MOTTLING.

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PLATE XV.

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PLATE XV.

PHOTOMICROGRAPHS OF FERRUGINOUS CHERT SHOWING LATER STAGES OF THE ALTERATION OF GREENALITE GRANULES.

FIG. *A*.—Ferruginous chert with granules. Specimen 45003, slide 15563. From near center of sec. 22, T. 60 N., R. 13 W. Without analyzer, x 50. The granules are outlined and in part replaced by iron oxide. The matrix is chert. The complex nature of one of the granules is to be noted. Apparently one complete small granule is entirely inclosed in another large one. Described pp. 116–120.

FIG. *B*.—Grünerític ferruginous chert. Specimen 45003, slide 15974. From Clark mine. With analyzer, x 50. The rock consists of chert and iron oxide and grünerite. The iron oxide is a yellowish-brown hydrated variety, which is with difficulty distinguished from the grünerite. The granules have been entirely obliterated. Described pp. 116–120.

FIG. *C*.—Ferruginous chert with granules. Specimen 45183, slide 15657. From 400 paces north, 35 paces west, sec. 28, T. 59 N., R. 15 W. Without analyzer, x 50. The rock consists almost entirely of chert with a small amount of iron oxide. The granules are marked by a light pigment which on a hurried examination would be scarcely noticed. Described pp. 116–120.

FIG. *D*.—The same under crossed nicols. The cherty nature of the rock is here shown, and the granules are quite obscured by the double refraction of the chert. Described pp. 116–120.

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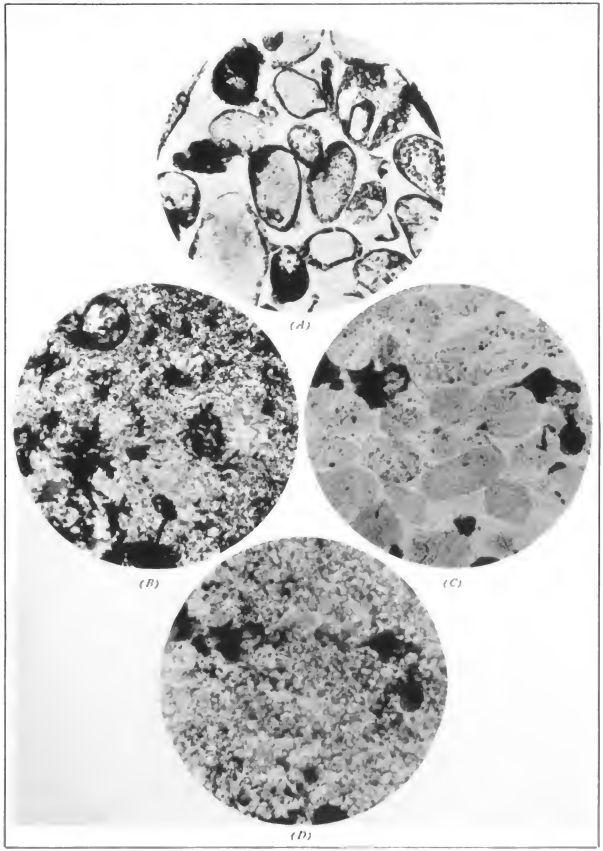

PHOTOMICROGRAPHS OF FERRUGINOUS CHERT SHOWING LATER STAGES OF THE ALTERATION OF GREENALITE GRANULES.

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PLATE XVI.

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PLATE XVI.

PHOTOMICROGRAPHS OF FERRUGINOUS CHERT OF PENOKEE-GOGEBIC DISTRICT.

FIG. *A*.—Concretionary chert. Specimen 9048, slide 2886. From Penokee-Gogebic district. Without analyzer. These are the normal concretions from the Penokee-Gogebic district supposed by Van Hise to be secondary developments during the alteration of an iron carbonate. (Pl. XXII, fig. 1, Mon. U. S. Geol. Survey Vol. XIX. Described on pp. 227 and 228 of Mon. XIX.)

FIG. *B*.—Ferruginous chert. Specimen 9625, slide 3150. From Penokee-Gogebic district. Without analyzer, x 60. The granules here shown are identical in aspect with granules in the Mesabi iron formation which can be shown to have developed from greenalite. (Reproduced from Pl. XXVII, fig. 2, Mon. U. S. Geol. Survey Vol. XIX.)

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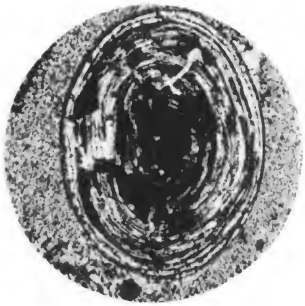
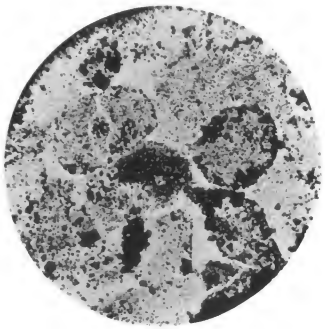


(A)



(B)

PHOTOMICROGRAPHS OF FERRUGINOUS CHERT OF PENOKEE-GOGEBIC DISTRICT.

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PLATE XVII.

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cherts as due to the strain incident to the change of volume during the alterations which the rock has undergone. Certain of the brecciated phases in higher horizons of the formation might be thus explained, but the persistent belt at the base is evidence of more concentrated movement along one horizon than could be attributed to chemical strains.

Another phase closely associated with the above-described jaspery phase and characteristic of the lower horizon of the iron-bearing formation is a dense purplish-red chert in which the characteristic granules are very slightly differentiated by a somewhat lighter red or purple color. Under the microscope the rock appears as a fine-grained chert with granules marked by iron oxide, largely hematite and magnetite, sometimes arranged peripherally. The rock differs from the jaspery rock above described only in lacking the gnarled and contorted minute bandings and in containing less clear quartz.

A rare rock associated with the ferruginous chert is composed of interbanded chert, iron, and greenish-yellow material which is partly chlorite, in the form of delessite, and partly serpentine. This may be observed in the Fayal mine.

The ferruginous chert in several places exhibits ellipsoidal nodules with their greater diameters in the plane of bedding. They may be well observed in the railway approach of the Oliver mine. They reach a diameter of 6 inches, although commonly they are smaller than this. The nodules consist of ferruginous chert similar to that in the layers adjacent, differing only in being more massive and perhaps somewhat finer grained. The layers apparently do not continue through the nodules. Some of them abut against the nodules and others bend slightly in passing by. The nodules are similar to those in the overlying Virginia slate and to those found in slates and cherts in general.

Still another type which should be specially mentioned is one which frequently occurs in the neighborhood of iron-ore deposits, a dense yellow chert owing its color to limonite. (Fig. *A* of Pl. XL.) Under the microscope there appear granules with unusual characters. In ordinary light they are practically colorless; under cross nicols they are almost isotropic, but show yellow polarization colors in minute spots, indicating incipient crystallization of quartz and perhaps other minerals. The matrix, at first glance, is apparently composed entirely of yellow limonite, but a high

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power reveals in addition the presence of abundant grünerite or actinolite in typical sheaf-like and radial forms.

The ferruginous cherts rarely contain a considerable amount of iron pyrites. The "gold mine," 600 steps west of the southeast corner of sec. 29, T. 60 N., R. 13 W., is a good example. The ferruginous chert is here a dark-gray and black, fine-grained, siliceous rock, in which the shapes of the greenalite granules can be easily distinguished, although the granules have been completely altered to chert. The iron pyrites occurs in large crystals, replacing all the other constituents of the rock, and also as a filling in the interstices between the granules, and marking the outlines or even partially replacing the granules. The iron pyrites in this case has crystallized during or subsequent to the alteration of the granules.

An occasional rock may be seen to consist of a dense felted mass of dark-green and brown amphibole, which is probably grünerite or cummingtonite, interbanded with carbonate of iron or calcium, or containing carbonate in rhombs, which frequently show a beautiful zonal alteration in their interiors.

Chemically the cherts show wide variation. Comprising, as above described, rocks consisting almost entirely of silica, rocks consisting very largely of iron oxide, and rocks of intermediate kinds, with greatly varying quantities of associated minerals, the variety of results in the analyses listed below is to be expected. The analyses in the following table are of cherts lacking any large amount of amphibole. The analyses of the cherts rich in amphibole are given in a separate table. A part of the analyses are incomplete. Dotted lines indicate that the substances have not been looked for, not their absence.

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Analyses of ferruginous cherts.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
SiO_2	63.92	32.56	77.60	80.93						
Al_2O_3	None.	None.								
Fe_2O_3	31.13	66.02								
Fe	24.22	46.45	14.78	9.69	25.25					3.43
FeO	3.13	.30								
MgO	.49	None.								
CaO	None.	.18								
Na_2O	Trace.	None.	.12							
K_2O										
H_2O-	.48	.32								
H_2O+	1.12	.90								
TiO_2	Trace.	.16								
CO_2	None.	None.								
P_2O_5	.05	.12								
P	.021	.052	None.	.006	.021	.020	.023	.026	.062	.009
SO_3	None.	None.								
MnO	.10	.14								
Loss on ignition										

	11.	12.	13.	14.	15.	16.	17.	18.	19.	20.
SiO	45.49		95.73	63.68			85.97	57.00	61.57	86.35
Al_2O_3							.67	1.43	16.83	.78
Fe_2O_3							11.40	27.05	5.27	7.41
Fe	33.61	53.53	1.72	19.53		51.41				
FeO							.80	11.08	6.41	3.46
MgO							.02	2.02	3.44	.05
CaO							.01	.40	.01	.01
Na_2O							.01	.397	.12	.12
K_2O			None.				.01	.113	1.59	.01
H_2O-							.30		4.70	.01
H_2O+										
TiO_2										
CO_2										1.22
P_2O_5					.03	5.70				
P	.013	.025	Trace.	.019	.0129	2.49				
SO_3										
MnO										
Loss on ignition								.91		

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1. Ferruginous chert below horizon of ore deposit (specimen 40751); from sec. 28, T. 58 N., R. 17 W., north of Virginia. Analysis by Geo. Steiger.

2. Ferruginous chert in horizon of ore deposits (specimen 40744); from Oliver mine. Analysis by Geo. Steiger.

3. Ferruginous chert showing red granules (specimen 45662); from pit in southwest of sec. 3, T. 58 N., R. 17 W. Analysis by E. T. Allen.

4. Ferruginous chert, basal phase with red granules (specimen 45688); from outcrop on Sparta road just east of Fayal mine. Analysis by R. B. Green.

5. Ferruginous chert (average of cores in several holes from beneath ore deposit); from Donora mine. Analysis by Lerch Bros.

6. Ferruginous chert (specimen 45690); from beneath ore deposit in NE. ¼ of NE. ¼ sec. 11, T. 57 N., R. 21 W. Analysis by Lerch Bros.

7. Ferruginous chert (specimen 45596); from just above slate in pump shaft of Penobscot. Analysis by Lerch Bros.

8. Ferruginous chert (specimen 45589); from north wall of Mahoning mine. Analysis by Lerch Bros.

9. Ferruginous chert (specimen 45543); from northwest of Mesabi Chief mine. Analysis by Lerch Bros.

10. Ferruginous chert (specimen 45672 B); from Donora mine. Analysis by Lerch Bros.

11. Ferruginous chert, hard bluish gray, seen grading into blue and black ore (specimen 45694); from Biwabik mine, east end. Analysis by R. B. Green.

12. Ferruginous chert within ore deposit; from Adams mine.

13. Ferruginous chert, green, banded, siliceous (specimen 45653); from south of Virginia along Duluth, Missabe, and Northern tracks. Analysis by E. T. Allen.

14. Ferruginous chert, hard yellow, seen grading into limonite (specimen 45692); from Biwabik mine, east side. Analysis by R. B. Green.

15. Ferruginous chert, yellow (specimen 45603); from Clark mine. Analysis by H. N. Stokes.

16. Ferruginous chert, in middle horizon; from NE. ¼ sec. 21, T. 59 N., R. 14 W. Analysis by Lerch Bros.

17. Ferruginous chert (specimen 65, chem. series No. 237). Analysis by C. F. Sidener, for J. E. Spurr. (See Geol. Nat. Hist. Survey Minnesota, Bull. No. 10, p. 116.)

18. Ferruginous chert (specimen 107, chem. series No. 243); from SW. ¼ of SW. ¼ sec. 2, T. 58 N., R. 19 W. Analysis by A. J. Hammond, for J. E. Spurr. (See Geol. Nat. Hist. Survey Minnesota, Bull. No. 10, p. 134.)

19. Ferruginous chert, top of Biwabik formation (specimen 101, chem. series No. 239); from SE. ¼ of NW. ¼ sec. 18, T. 58 N., R. 18 W. Analysis by Alonzo D. Meeds, for J. E. Spurr. (See Geol. Nat. Hist. Survey Minnesota, Bull. No. 10, p. 148.)

20. Ferruginous chert, Biwabik formation (specimen 27 A, variety 1); from sec. 33, T. 58 N., R. 17 W. Analysis by C. F. Sidener, for J. E. Spurr. (See Geol. Nat. Hist. Survey Minnesota, Bull. No. 10, p. 54.)

It is apparent from the above that the ferruginous cherts grade from almost pure cherts to iron ore. The percentage of phosphorus is uniformly lower than that of the ores (see pp. 214–217). The ferric iron is greatly in excess of the ferrous iron; calcium and magnesium oxides are rare; carbon dioxide is almost entirely absent. Another characteristic feature which is not emphasized by the analyses is the presence of organic matter. The loss on ignition consists partly of the oxidation of organic matter, according to chemists who have handled the Mesabi ores (see p. 218). The content of organic matter is not so great in the ferruginous cherts as in the slates.

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The cherts in which the amphibole constituent is abundant show composition different from that of the cherts above analyzed.

Analyses of amphiboditic cherts.

	Specimen 45028.	Specimen 45648.	Specimen 45649.	Specimen 45689.
SiO_2 (total)	50.36	83.82	23.94	44.10
SiO_2 (soluble in HCl)	18.42	3.52	12.76	15.93
Al_2O_3	.64	.39	6.00	1.05
Fe_2O_3	6.46	4.46	5.81	10.80
FeO	[a] 32.91	8.77	34.29	28.73
MgO	3.94	None.	5.05	2.43
CaO	.23	.60	1.51	.33
Na_2O	None.	None.	.28	None.
K_2O	None.	None.	None.	None.
H_2O-	.27	.13	.....	.51
H_2O+	4.64	1.37	.....	2.47
TiO_2	None.	None.	.41	None.
CO_2	None.	.72	18.03	9.71
P_2O_5	None.	.02	.11	.04
SO_3	None.	.....	.....	.....
S	None.	.....	.....	.....
MnO	None.	None.	.....	None.
BaO	None.	.....	.....	.....
Carbon in organic matter	.18	.....	.....	.....

[a] Owing to presence of organic matter the determination of ferrous iron is probably high.

Specimen 45028; from old Chicago mine in NE. ¼ of SE. ¼ of sec. 4, T. 58 N., R. 16 W. Analysis by George Steiger.

Specimens 45648 and 45649; from pit near Duluth, Missabe and Northern track, about one-half mile south of Virginia. Analysis by George Steiger.

Specimen 45689; from Donora mine, near the east side of sec. 28, T. 59 N., R. 15 W. Analysis by George Steiger.

In these four samples the amphibole is mainly dark brown or dark green, with inclined extinction, which might, from its microscopic character, be common hornblende, cummingtonite, or grünerite, but it is in part also colorless or nearly colorless actinolite. The lack of alumina shows that it is not hornblende. In all there is a small amount of iron oxide to be seen in the slide. In specimens 45649 and 45689 siderite is abundant. In strong hydrochloric acid a considerable amount of the dark material was dissolved out, leaving a white residue in specimens 45028

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and 45648, and a dark residue in specimens 45649 and 45689. It seems probable that the dark amphiboles and the iron oxide are the substances which are mostly dissolved by the hydrochloric acid. The analyses give results which accord with the microscopic observations. The ferrous iron present, except that combined with the carbon dioxide to form siderite, may be supposed to be mainly combined with silica to form grünerite, the magnesium and calcium oxides to be combined with the silica to form actinolite, or the ferrous iron and the magnesium and calcium oxides to be combined with silica to form cummingtonite. In three of the analyses magnesia is present in much higher percentage than calcium oxide.[a] In the analyses of the greenalite rock on page 108 and of the amphibolitic slates on pages 144–145 the same fact may be noted. The principal amphiboles containing such a ratio of magnesium oxide to calcium oxide are anthophyllite and cummingtonite, both of which are essentially silicates of magnesium and ferrous iron. The amphibole in the Mesabi rocks does not have the optical properties of anthophyllite, but has properties ranging from those characteristic of actinolite to those characteristic of grünerite or cummingtonite. The high proportion of magnesium oxide to calcium oxide would indicate, therefore, that the dark-colored amphibole is at least in part cummingtonite. The above analyses show a lower percentage of combined water than obtains in the analyses of unaltered greenalite granules discussed on preceding pages, and it is apparent that the development of the amphiboles has involved dehydration of the original greenalite.

The direct development of dark amphibole from the greenalite may be well observed in specimen 45689, where the change from the greenalite apparently has been merely a matter of the fine recrystallization of the original substance. The change is scarcely noticeable in ordinary light, and under crossed nicols is shown only by the low double refraction. In the slide no actinolite is to be observed. The matrix is chert. The carbon dioxide is supposed to be combined with the lime, magnesia, and a part of the ferrous iron; the carbonate can be observed in the slide. The remainder of the ferrous iron, together with the small amount of magnesium oxide

[a] In this connection it is of interest to note that an analysis of a grünerite-magnetite-schist from the Marquette district, given by Van Hise, shows a similar high proportion of magnesium to calcium. (Mon. U. S. Geol. Survey Vol. XXVIII, p. 338, Analysis No. 3.) Also an analysis of grünerite by Lane and Sharples shows a high percentage of magnesium and a lack of calcium. (Am. Jour. Sci., 3d series, Vol. XLII, 1891, p. 506.) The analyses suggest that the amphibole may be more closely allied with cummingtonite than grünerite.

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present, may be supposed to be combined with the soluble silica shown in the analysis to form the dark amphibole. The ferric iron and water are combined to form limonite, which may be observed in the slide. This would leave 17.60 per cent of FeO, and 15.93 per cent of soluble SiO_2. On the basis of 100 the proportions are FeO 52.5 per cent, SiO_2 47.5 per cent, which shows the green substance to be closely allied to grünerite. These figures show a proportion of ferrous iron and silica similar to that shown in the analyses of the unaltered green granules. They differ in showing less combined water. This similarity is in accord with the microscopic observation that the amphibole has developed by simple recrystallization of the original green granules.

SILICEOUS, FERRUGINOUS, AND AMPHIBOLITIC SLATES.

Under this head are grouped a variety of slaty rocks which are interstratified with the other phases of the iron formation. They include dense, black, dark-gray, green, or reddish rocks with a tendency toward conchoidal fracture, and the slaty parting poorly developed if at all; rocks showing banding of dark-green, black, gray, red, or brown layers parallel to the bedding, and a well-developed cleavage parallel to the same structure; gradational varieties between these two, between them and the ferruginous cherts, and between them and the iron ores (Pl. XVIII, figs. *B* and *C*). Any of them may be hard or soft, carbonaceous or noncarbonaceous, fine grained or medium grained.

Under the microscope the slates are seen to contain principally cherty quartz, iron oxide, either hematite or magnetite, usually in octahedra, or some hydrated oxide, monoclinic amphibole which may be grünerite, cummingtonite, or actinolite, and possibly even common hornblende, a small amount of carbonate of calcium or iron, a little zoisite, and possibly, also, a little chlorite. From the optical properties, and from the analysis of the rock, it is thought that the amphibole is mainly grünerite and cummingtonite. There is much variation in the relative proportion of the principal constituents. Some of the slates consist almost entirely of fine cherty quartz with subordinate quantities of dark amphibole in radial aggregates or in irregular masses and of the iron oxides. Others are composed mainly of iron oxide, showing but small quantities of the quartz and dark amphibole. Others are composed of a tangled mass of yellowish, brownish,

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and greenish amphibole fibers containing minute particles of iron oxide, silica, and other subordinate constituents. The grünerite is far more abundant than the actinolite. The banding frequently shown in a specimen is due to the segregation of the above-named elements into layers. While it may be convenient in description to refer to this or that slaty rock as a ferruginous slate, a siliceous slate, an amphibolitic slate, or an actinolite slate, depending upon the relative abundance of the constituents, usually all three constituents are present in one rock, and the rocks are really amphibolitic, siliceous, and ferruginous slates. Perhaps the most characteristic feature of the slates as a group is the abundance of the dark amphibole.

Corresponding to the mineralogic variation in the slates there is considerable chemical variation, as shown by the following partial analyses of most of the phases of the slaty rocks. Dotted lines indicate that the substances have not been looked for, not their absence.

Analyses of siliceous, amphibolitic, and ferruginous slates within the Biwabik formation.

	1.	2	3.	4.	5.	6	7
SiO_2	37.11	44.22	48.16	.....	53.86	35.12	37.01
Al_2O_3	2.41	6.39	.....	.....	9.14	1.72	2.16
Fe_2O_3	17.51	.....	.....	.....	.....	.....	.....
Fe	.....	22.20	24.53	29.90	15.90	42.18	41.00
FeO	26.13	.....	.....	.....	.....	.....	.....
MgO	3.70	.....	.....	.....	.....	.....	.....
CaO	.75	.....	.....	.....	.....	.....	.....
Na_2O	.09	.....	.....	.....	.....	.....	.....
K_2O	.62	.....	.....	.....	.....	.....	.....
H_2O-	.95	.....	.....	.....	.....	.....	.....
H_2O+	2.57	.....	.....	.....	.....	.....	.....
TiO	.22	.....	.....	.....	.....	.....	.....
CO_2	6.16	12.60	.....	.....	.14	.....	.....
P_2O_5	.09	.05	.....	.....	.04	.....	.....
P	.....	.....	.004	.008	.....	.036	.022
SO_3	None.	.....	.....	.....	.....	.....	.....
MnO	1.21	.....	.....	.....	.....	.11	.17
Mn	.....	.....	.....	.....	.....	.....	.....
C	.73	.....	.....	.....	.....	.....	.....
Vol	.....	.....	.....	.....	.....	1.30	1.15
Loss on ignition	.....	.....	.....	.....	.....	.....	.....

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Analyses of siliceous, amphibolitic, and ferruginous slates within the Biwabik formation—Continued.

	8.	9.	10.	11.	12.	13.
SiO_2	12.93					23.80
Al_2O_3						7.95
Fe_2O_3						5.97
Fe	54.81	3.88	3.40			
FeO						32.21
MgO						5.89
CaO						4.67
Na_2O						.29
K_2O						.18
H_2O − } H_2O + }						4.28
TiO						
CO_2						11.84
P_2O_5	.012			.14		
P		.009	.010	.06	None.	
SO_3						
MnO						
Mn						Trace.
C		11.34				
Vol						
Loss on ignition						3.35

1. Specimen 45461, from Moss mine. Analysis by Geo. Steiger.
2. Specimen 45561, from Penobscot mine, 278 feet below taconite. Analysis by H. N. Stokes.
3. Specimen 45670, from sec. 7, T. 58 N., R. 18 W. Analysis by R. B. Green.
4. Specimen 45672 A, from Domora mine. Analysis by Lerch Bros.
5. Specimen 45600, from near southeast corner of NE. ¼ of SW. ¼ sec. 21, T. 58 N., R. 20 W. Analysis by H. N. Stokes.
6. Specimen 45645, from cut south end of Mountain Iron mine. Analysis by A. T. Gordon.
7. From cut south end of Mountain Iron mine. Analysis by A. T. Gordon.
8. Specimen 45677, from Adams mine. Analysis by R. B. Green.
9. From north of Little Mesabi exploration. Analysis by Lerch Bros.
10. Specimen 45672, from Domora mine. Analysis by Lerch Bros.
11. Specimen 45625, from northeast of Buhl. Analysis by H. N. Stokes.
12. Specimen 45678, from south of Spruce mine. Analysis by E. T. Allen.
13. Specimen 172 (Chem. Series No. 240) NE. ¼ of SE. ¼ of sec. 17, T. 58, R. 19 W. Analysis by A. D. Meeds, for J. E. Spurr. (See Geol. Nat. Hist. Survey Minnesota, Bull. No. 10, p. 10).

The essential features above shown are the variation in metallic iron, the considerable content of ferrous iron as compared with the ferric iron, low alumina as compared with true slate, but high as compared with the other rocks of the iron formation, and the greatly varying quantities of

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carbon dioxide and carbon, both of them, however, fairly abundant. The large proportion of magnesium oxide and calcium oxide accords well with the microscopic determination of some of the dark amphibole as cummingtonite.

In texture and in mineralogic and chemical composition the slaty rocks of the iron formation differ from true black roofing slates, such, for instance, as those from Vermont. The cleavage is not as good as in roofing slates, and what there is of it is parallel to the bedding and largely conditioned by the bedding, and not by the deformation of the rocks. Grünerite is abundant, while in typical roofing slates micaceous and chloritic constituents are important. Finally, the percentage of iron, and in some cases the percentage of silica, is higher, and the percentage of alumina is much lower than in typical slates. The slates in the iron formation also differ from the overlying Virginia slates in a manner described in connection with the latter (see p. 176).

Some of the typical occurrences of slate within the iron formation from which specimens have been collected are specified below:

The pump shaft of the Penobscot mine in sec. 1, T. 57 N., R. 21 W., passes through 278 feet of ferruginous chert and bottoms in slate (specimens 45591 to 45593).

Northeast of the center of sec. 27, T. 58 N., R. 20 W., E. J. Longear drilled through 56 feet of iron-formation material, mainly ferruginous chert, to slate (specimen 45600).

Test pit in the NE. ¼ of SE. ¼ sec. 17, T. 58 N., R. 19 W. (specimen 45630).

Drill hole in the NE. ¼ of NW. ¼ sec. 20, T. 58 N., R. 19 W. (specimen 45541).

Test pit in NE. ¼ of SW. ¼ sec. 10, T. 58 N., R. 19 W. (specimen 45625).

Test pit just southeast of northwest corner of sec. 8, T. 58 N., R. 18 W. (specimens 45639 and 45640).

Test pit and drill hole in the NW. ¼ of NW. ¼ sec. 7, T. 58 N., R. 18 W. (specimen 45670).

Test pit south of Virginia, west of the Duluth, Missabe and Northern track in the SE. ¼ of SW. ¼ sec. 8, T. 58 N., R. 17 W., near contact with the overlying Virginia slate (specimen 45652).

Test pit just north of the old Norman open pit in the SE. ¼ of NW. ¼ sec. 9, T. 58 N., R. 17 W. (specimens 40741 and 40742).

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Test pits south of the Spruce mine in NW. ¼ of NE. ¼ sec. 6, T. 57 N., R. 17 W. (specimen 45678).

Drill hole in Fayal mine. Slate reached under 200 feet of ferruginous chert (specimen 45734).

Test pit just south of the Elba mine near the north line of the NE. ¼ of NE. ¼ sec. 24, T. 58 N., R. 17 W. (specimen 40863).

Test pits and shafts of the old Chicago mine in the NE. ¼ of SE. ¼ sec. 4, T. 58 N., R. 16 W., near contact with overlying Virginia slate.

Test pits in the Cincinnati mine in the SW. ¼ of NE. ¼ sec. 2, T. 58 N., R. 16 W., and the SE. ¼ of NW. ¼ sec. 2, T. 58 N., R. 16 W., near contact with overlying slate (specimen 45039).

Test pit and drill hole in SE. ¼ of NE. ¼ sec. 28, T. 59 N., R. 15 W., the little Mesabi exploration (specimen 45672).

Test pits in the SE. ¼ of SE. ¼ sec. 22, T. 59 N., R. 15 W. (specimen 45175).

Test pit in SW. ¼ of SW. ¼ sec. 26, T. 59 N., R. 15 W. (specimen 45737).

Test pit in SE. ¼ of NW. ¼ sec. 28, T. 59 N., R. 15 W. (specimen 45191 calcareous).

Drill hole in the SE. ¼ of NE. ¼ sec. 19, T. 59 N., R. 14 W. (specimen 45003).

Drill hole in the SW. ¼ of SW. ¼ sec. 16, T. 59 N., R. 14 W. (specimen 45006).

Test pit in the NW. ¼ of SW. ¼ sec. 21, T. 59 N., R. 14 W. (specimens 45009 and 45010).

Test pits in SW. ¼ of SW. ¼ sec. 15, and NW. ¼ of NW. ¼ sec. 22, T. 59 N., R. 14 W. (specimens 45224 and 45228).

Exposure (?) NE. ¼ of SE. ¼ sec. 21, T. 59 N., R. 14 W. (specimen 45699).

Exposure (?) east of the west quarter post of sec. 22, T. 59 N., R. 14 W. (specimen 45700.)

From near the east side of range 14 eastward through ranges 13 and 12 the slates interbedded with iron formation are in great abundance, and, because of the good exposure of the rocks in this area, can be well observed. One may mention in particular the belt extending north and east of Mallman camp (see map, Pl. VI), and the slate along the road in the NE. ¼ of sec. 1, T. 59 N., R. 14 W.

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It has been maintained by certain of the mining engineers on the Mesabi range that the slates found within the area of the iron formation represent, in large part, patches of the Virginia slate, which, in these particular places, have been left as islands during the erosion which removed most of the slate from the area. The area is heavily drift covered, and the slates are, for the most part, found in isolated explorations and show no relations to surrounding rocks. It is possible that the occurrence of some small part of the slate may be explained in this way, but it is believed that practically all of it is interstratified with the iron formation, for the following reasons:

(1) In a number of places explorations have gone through the iron formation into the slate, and then into iron formation again. Also, in the east end of the district actual interbedding can be observed in exposures.

(2) As the iron formation and Virginia slate are conformable and have the same dip, patches of the Virginia slate left on top of the iron formation, especially where well to the north, must necessarily have a considerably higher elevation than the surrounding rock surface. So far as can be ascertained under the thick covering of drift, the slates in the iron formation are not elevated above the surrounding rock surface.

(3) Commonly, where exploration has gone far enough, the slate in the iron formation is found to come to the rock surface in a narrow band, with strike parallel to the strike of the iron formation layers, and not in an irregular patch with outlines determined by erosion.

(4) In mineralogic and chemical composition the slate layers within the iron formation are somewhat different from the Virginia slate. (See p. 176.)

It is not improbable, indeed it is likely, that certain of the interstratified slate layers in the iron formation have been mapped as Virginia slate; that is, where full data have been absent the Virginia slate boundary has been extended to the north to cover slate shown in some exploration which may really be a layer of slate interstratified in the iron formation. If this is true, future work will result in carrying the Virginia slate boundary farther south.

As ore deposits have not been found to occur under the solid Virginia slate, and as the slate layers in the iron formation have an influence on the concentration of the ore deposits later discussed, it is apparent that the discrimination of the various slates is a matter of importance to mining men.

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PAINT ROCK.

Throughout the iron formation, and particularly adjacent to the ore deposits, are thin seams of paint rock, which have resulted from the alteration of the slates above described. The paint rocks are essentially soft red or yellow or white clay. They retain the original bedding of the rocks from which they were derived, the structure being marked by alternation of bands of different color. In situ the paint rocks are moist and soft. When taken out and dried they become harder, but retain a soft, greasy feel.

The alteration of the paint rocks from slates is proved by the numerous intermediate phases to be observed. (See Pl. XVIII.) At several mines also the paint rocks associated with the ore deposits are in the same horizon as slates immediately adjacent. At the Penobscot mine paint rock forms a persistent horizon near the bottom of the mine, while the pump shaft sunk in the adjacent rock struck slate at the same horizon. At the Biwabik mine there is a capping of paint rock over the ore, which, according to the superintendent, has been found by test pitting to grade southward into the true black slate mapped as Virginia slate. South of the exploration of the Medow Mining Company in the NW. ¼ of sec. 3, T. 58 N., R. 15 W., a considerable quantity of paint rock is encountered along the north margin of the Virginia slate. Other instances might be cited, but the proof is so conclusive at these places that further evidence is hardly necessary. Chemically, the paint rocks have the characteristics shown in the following partial analyses:

Analyses of paint rock.

	1.	2.	3.	4.	5.	6.	7.	8.
SiO_2	9.54	55.57					32.16	20.94
Al_2O_3	7.00	3.28	6.58	7.75	7.62	7.23	31.39	19.01
Fe_2O_3	77.30	30.57						
FeO	.45							
Fe		25.60	54.20	47.49	47.48	56.72	17.56	30.88
TiO_2	.61							
H_2O-							9.55	13.40
H_2O+								
CO_2		None.						
P_2O_5	.20	Trace.						
P			.055					

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1. Paint rock (specimen 40661) from Mahoning mine. Analysis by George Steiger.
2. Paint rock (specimen 45594) from Penobscot mine, beneath ore. Analysis by H. N. Stokes.
3. Paint rock from Franklin mine. Analysis by E. F. Johnson.
4. Paint rock from Wacoutah property near Mountain Iron. Analysis by Lerch Bros.
5. Paint rock from Wacoutah property near Mountain Iron. Analysis by Lerch Bros.
6. Paint rock from Wacoutah property near Mountain Iron. Analysis by Lerch Bros.
7. Light portion of banded red and white paint rock (specimen 45646) from Mountain Iron mine. Analysis by A. T. Gordon.
8. Dark portion of banded red and white paint rock (specimen 45646) from Mountain Iron mine. Analysis by A. T. Gordon.

SIDERITIC AND CALCAREOUS ROCKS.

Associated with the slaty layers in the iron formation, and particularly with the greenalite rocks, are carbonates of iron and calcium in small quantity. Most of the carbonate reacts readily with cold dilute hydrochloric acid and is certainly limestone, which, from the analysis of rocks containing it, is doubtless magnesian. Some of the carbonate, however, is certainly siderite, as shown by the analysis on page 141. The carbonates occur in minute clear-cut layers interbedded with the iron formation (see Pl. XIII, fig. *A*), in veins cutting across the bedding, in irregular aggregates in iron formation layers, and in well-defined rhombohedral crystals in the same. In the carbonate bands are small quantities of iron oxide, ferrous silicate, and chert, and in the bands of these minerals are small quantities of the carbonate. In some cases the carbonates are coarsely crystalline and fresh and clearly have resulted from the replacement of the other constituents in the rock, particularly the ferrous silicate, or from infiltration along cracks and crevices. In other cases, especially where in distinct layers interbedded with unaltered ferrous silicate phases of the formation, the carbonate layers seem certainly to be original. At the top of the iron formation and closely associated with the basal horizons of the Virginia slate are several feet of clear calcium carbonate, which is described in connection with the Virginia slate.

North of Birch Lake is a siliceous and sideritic slate exposed in one pit. (See fig. 7, p. 184.) The carbonate is a peculiar grayish banded slate, which near the surface and adjacent to cracks is weathered to a rusty-brown color. The weathering penetrates several inches from the surface. Under the microscope the rock is seen to be largely made up of carbonate in bands and in isolated rhombs associated with magnetite and chert. The rusty weathering of the carbonate and the fact that it effervesces but slightly, if at all, with cold hydrochloric acid indicate it to

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PLATE XVIII.

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PLATE XVIII.

SLATE, FERRUGINOUS SLATE, AND PAINT ROCK IN IRON FORMATION AND CONTACT OF IRON-BEARING FORMATION WITH INTRUSIVE GRANITE.

FIG. *A*.—Contact of Biwabik formation and Embarrass granite. Specimen 45538. From the NW. ¼ sec. 17, T. 60 N., R. 12 W. Natural size. The granite is in intrusive contact with the iron formation. Note the purple quartz phenocrysts in both. Described pp. 186–188.

FIG. *B*.—Banded slate. Specimen 45592. From Penobscot mine, 298 feet below ferruginous chert. Natural size. Described pp. 143–148.

FIG. *C*.—Banded ferruginous slate. Specimen 45594. From Penobscot mine, 298 feet below ferruginous chert. Natural size. Described pp. 143–148.

FIG. *D*.—Paint rock. Specimen 45587. From north wall of the Mahoning mine. Natural size. The derivation of the paint rock from the alteration of slate is evident. Many specimens have been collected showing complete gradation between the two. Described pp. 149–150.

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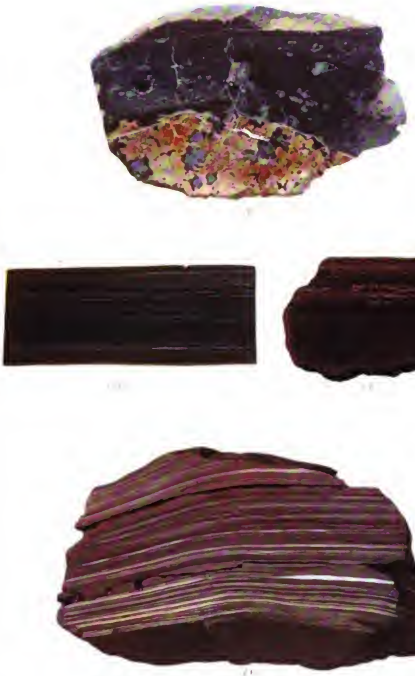

be an iron carbonate or siderite. The siliceous phase of the slate is clearly a replacement of the carbonate. Indeed in hand specimens it is almost identical in appearance It is a minutely banded gray and black and brown rock with a poor parting parallel to the banding. Under the microscope it is seen to have a medium-grained, quartzose background, in which are octahedra of magnetite. The concentration of the iron oxide and the quartz in alternate bands gives the minute banding observed in the hand specimen.

An analysis of the rock (specimen 45161) by George Steiger is as follows:

Analysis of siliceous slate of iron formation at contact of gabbro.

	Per cent.
SiO_2	78.95
Al_2O_3	None.
Fe_2O_3	13.89
FeO	1.23
MgO	.18
CaO	.81
Na_2O	None.
K_2O	None.
H_2O-	.73
H_2O+	2.21
TiO_2	None.
CO_2	1.59
P_2O_5	.04
SO_3	None.
MnO	.11
Total	99.74

The rock analyzed is from the same mass as the carbonate, and before analysis was supposed itself to be partly carbonate.

The total absence of any traces of greenalite granules and the occurrence of the carbonate in well-bedded layers, evidently little altered, make it probable that the sideritic slate at Birch Lake is original. It is the nearest approach in nature and abundance to the original sideritic slates characteristic of the Penokee-Gogebic range to be anywhere seen on the Mesabi range. Eastward, in the neighborhood of Gunflint Lake, structures characteristic of the alteration of siderite are to be observed Its occurrence at the east end of the district, together with certain structures in the Gunflint Lake region to the east characteristic of altered sideritic rocks, is suggestive of a gradation toward the east to phases characteristic of the Penokee-Gogebic iron formation.

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CONGLOMERATES AND QUARTZITES.

At the base of the iron formation is a thin layer of fairly coarse fragmental material consisting in places of conglomerate alone and in other places of conglomerate and quartzite. At several localities the full succession from the iron formation above through the quartzite or conglomerate, or both, into the Pokegama quartzite below may be studied. In the SW. ¼ of SW. ¼ of sec. 3, T. 58 N., R. 17 W. (see fig. 3, p. 89) are a considerable number of test pits which have either been bottomed in the quartzite belonging to the iron formation or have gone through this and have been bottomed in the Pokegama quartzite. At the Fayal and Adams mines green quartzites are found beneath the ferruginous chert, and so closely resemble it that they were classed as "taconite" by the drillers. Drill holes on the NE. ¼ of the SE. ¼ of sec. 4, T. 58 N., R. 16 W., put down by E. A. Sperry, penetrated the iron-formation conglomerate (45753), Pokegama quartzite, and Lower Huronian rocks, in the order named. One of the northward drifts of the Cincinnati mine penetrates the quartzite at the base of the iron formation. A little southwest of the center of sec. 18, T. 59 N., R. 14 W., is a trench in which may be observed the actual contact of the iron formation and the Pokegama quartzite. Here only the conglomerate appears at the base of the iron formation. In the S. ½ of SE. ¼ of sec. 29, T. 60 N., R. 13 W., the same thing may be observed in natural exposure. Here also the conglomerate alone is present at the base of the iron formation.

A drill hole put down by E. J. Longear in the SW. ¼ of SE. ¼ of sec. 32, T. 59 N., R. 17 W. penetrated iron formation, quartzite, conglomerate, and Pokegama quartzite in the order given. (Specimens 40851 to 40855.)

Thin films of conglomerate lie on the upper surface of the Pokegama quartzite a little north of the east quarter post of sec. 13, T. 58 N., R. 17 W.; just north of the Arcturus mine near the center of sec. 13, T. 56 N., R. 24 W.; at the falls of the Prairie River in range 25; and at Pokegama Falls in range 26.

On the dumps of a number of the pits adjacent to the northern boundary of the iron formation are found conglomerate and quartzite with such relations to the iron formation and the Pokegama quartzite as to show them to be basal to the iron formation. Some of these pits are located as

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follows: The NW. ¼ of SE. ¼ sec. 13, T. 58 N., R. 17 W. (specimens 46020 and 46021); in the NE. ¼ of SW. ¼ sec. 33, T. 58 N., R. 17 W. (specimen 46026); in the SE. ¼ of SE. ¼ sec. 5, T. 58 N., R. 16 W. (specimen 46034); in the SW. ¼ of SW. ¼ sec. 4, T. 58 N., R. 16 W. (specimens 46031 and 46032).

Finally numerous fragments of conglomerate, similar to the conglomerates at the base of the iron formation, were found in the drift in such a position as to show the probability of their having been carried to their present resting place from the contact of the iron formation and the Pokegama quartzite.

The quartzite is best exhibited in the pits in the SW. ¼ of SW. ¼ sec. 3, T. 58 N., R. 17 W. (fig. 3, p. 89), and a description of its character and occurrences here will suffice for the district. Several pits were cleaned out, and the succession carefully studied. In going down the first rock struck was a massive, somewhat vitreous, fine-grained quartzite, with green, brown, red, and yellow colors. The green quartzite is evidently the original form, and the red, brown, and yellow colors are due to iron staining or to bleaching. Microscopically, the green rock is observed to be composed of rounded and subangular grains of quartz and a subordinate amount of greenish-yellow granules of ferrous silicate like those in the ferruginous cherts above described. The matrix is composed of a dense greenish chloritic or ferrous silicate substance stained with iron ore. The alteration of this cement to iron oxide or the leaching out of its ferrous silicate constituent has given the red, brown, and yellow quartzites.

Beneath 10 or 12 feet of this kind of quartzite is a heavily ferruginous quartzite which is coarser, contains better rounded grains, a heavily ferruginous matrix, and is in places considerably softer. The well-rounded quartz grains stand out like eyes in the abundant, heavily ferruginous matrix. At certain of the pits the content of iron is so great that the rock looks like a soft ore, and indeed analysis shows it to come almost within the limit of merchantable ore. Under the microscope the quartz grains are seen to be well rounded, usually to show pressure effects by undulatory extinction, and sometimes apparently to be themselves composite—that is, to consist of several grains as though derived from a preexisting quartzite. In addition to the quartz, there are fairly numerous greenalite granules with characteristic greenish-yellow colors and showing

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considerable alteration to hematite, and small rounded grains composed of cherty quartz, sometimes with radial forms perhaps representing the alteration of the greenalite granules. The matrix is yellowish or reddish brown and consists mainly of hematite with a slight intermixture of greenish-yellow chloritic or ferrous silicate material. The heavily ferruginous quartzite is but a few feet thick. Partial analyses of both the green and heavily ferruginous varieties of quartzite are as follows:

Analysis of quartzites at base of Biwabik formation.

	1.	2.	3.	4.
SiO_2	18.26	76.96	77.82	84.21
Fe	54.12	6.80	7.96	2.42
K_2O	None.	.28	.15	.....
P_2O_5	None.	None.	.03	.....
P	.....	.....	.....	.015

1. Ferruginous quartzite at base of iron formation (specimen 45668) from pits southwest of sec. 3, T. 58 N., R. 17 W. Analysis by E. T. Allen.

2. Green quartzite at base of iron formation (specimen 45665) from pits southwest of sec. 3, T. 58 N., R. 17 W. Analysis by E. T. Allen.

3. Green quartzite at base of iron formation (specimen 45655) from pits in southwest of sec. 3, T. 58 N., R. 17 W. Analysis by E. T. Allen.

4. Green quartzite near base of iron formation (specimen 45687) from drill hole just east of Fayal mine. Analysis by R. B. Green.

Above, the ferruginous quartzite becomes irregularly interbedded with gnarled and contorted phases of the ferruginous chert described on page 120. Hand specimens were collected showing several interlaminated layers of the normal siliceous ferruginous chert and the heavily ferruginous quartzite. The two kinds of rock have a knife-edge contact (Pl XII, fig. *B*). The interbedded quartzite and chert are but a few feet thick. Immediately below appears conglomerate a foot to 18 inches in thickness, resting on the Pokegama quartzite.

In the east end of the range is another phase of quartzitic material basal to the iron formation. This is essentially a heavily ferruginous chert characteristic of the iron formation, but containing numerous well-rounded quartz grains (specimens 46070 and 45119).

The basal conglomerate of the iron formation is usually in firm contact with the underlying massive Pokegama quartzite, and is frequently seen

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adhering to the surface of such a quartzite after the softer overlying iron formation has been worn away by erosion. It sometimes grades into the iron formation above through the quartzite above described, and sometimes grades directly into the iron formation, the intermediate quartzite being lacking. The fragments vary in size from that of sand grains to 6 inches in diameter. The average size is perhaps an inch or less. The fragments consist of vein quartz, of quartzite like the Pokegama quartzite immediately subjacent, of a soft yellow limonitic slate, easily eroded and frequently represented in part by cavities in the conglomerate, and of a jaspery phase of the ferruginous chert sometimes approaching iron ore. In abundance the fragments stand in about the order named. Locally, however, the jasper fragments or the soft yellow slaty fragments may be more abundant than the others. The matrix is almost entirely quartzite in various degrees of consolidation, although usually fairly hard. In some of the associated rocks in which the jaspery fragments are abundant the matrix is chert, containing altered greenalite granules; but such rocks are believed to be mainly breccias, belonging with the gnarled and contorted jaspery basal phases of the ferruginous chert (pp. 121–122).

Both the nature and the relative abundance of the pebbles are peculiar in a conglomerate at this horizon. One would expect to find quartzite pebbles in greatest abundance, and is puzzled by the presence of the jaspery chert and the yellow slaty fragments. Indeed, in the early part of the field work it was assumed that these conglomerates, containing, as they do, phases of material resembling phases of the iron formation, must necessarily have come from above the iron formation, and it was not until they were actually observed in place at several localities that it could be believed that they represent the base of the iron formation. The scarcity of quartzite fragments is believed to be due to the breaking up of the sandstone, the unindurated equivalent of the Pokegama quartzite, into its constituent grains when attacked by the water which deposited the conglomerate. The unconformity between the conglomerate and the quartzite is so slight that it is certain that the sand now represented by the Pokegama quartzite was only weakly cemented at the time of the formation of the conglomerate, so that when attacked by the waters the rock was disintegrated into its constituent sand grains, and only rarely a large fragment remained. It has been noted that the abundant matrix of the conglomerate is composed of well-rounded

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quartz grains of remarkably uniform size. They are identical in size and character with the quartz grains of the underlying Pokegama formation, and were probably derived from the disintegration of the sandstone.

The yellow limonitic slate pebbles, it is believed, were derived from the exceedingly thin-bedded or fine shaly phases of the underlying Pokegama quartzite, and owe their yellow and soft character to partial replacement by iron from the immediately overlying iron formation. In the SW. ¼ of SW. ¼ sec. 3, T. 58 N., R. 17 W., these yellow fragments are abundant in the conglomerate, and in two of the pits close at hand it is found that the phase of the Pokegama quartzite immediately underlying is a fissile, almost shaly one, and that some of it has been altered in place to such an extent as to resemble the fragments in the conglomerate. It is apparent that but a small amount of further alteration would be necessary in this case to give the pebbles the characters they are now observed to have in the conglomerate.

In the Mesabi district, the jaspery fragments in the conglomerates do not have their counterparts in the underlying Pokegama formation, or in the Lower Huronian or Archean rocks, but similar rocks are known in the Lower Huronian and Archean rocks of other iron-bearing districts of Lake Superior, and may have been exposed in the past even in the Mesabi district, having been removed by erosion or covered up by later formations. It is not impossible that the pebbles may have been carried along the shore for long distances. The jaspers of the underlying formations in adjacent districts are much older than the conglomerate, and must have been almost as hard as at present at the time the conglomerate was formed. This being the case, they may have been transported for many miles along the shore without losing their integrity.

While the explanation of the nature and relative abundance of the fragments in the conglomerates may be in doubt in some cases, the position and relations of the conglomerate to the underlying and overlying series are certainly known. Enough evidence is at hand to warrant the statement that the base of the iron formation is conglomeratic or quartzitic, or both, throughout the district and that these fragmental rocks vary in thickness from a few inches to 15 or more feet. Their structural significance is discussed in the section on relations of the Biwabik formation to other formations.

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Conglomerates have not been found in middle or upper horizons of the Biwabik formation, except at one place. In the south wall of the Mahoning open cut a layer of conglomerate entirely altered to iron ore lies between layers of iron ore with normal texture.

THE ALTERATION OF THE IRON FORMATION BY THE INTRUSION OF KEWEENAWAN GRANITE AND GABBRO.

Through ranges 12 and 13 the iron formation is intruded on the north by granite and on the south by the Duluth gabbro (see map, Pl. II, and description, pp. 182–188), and has undergone considerable metamorphism in consequence. This metamorphism has extended even farther west, for, while the gabbro does not come into actual contact with the iron formation through range 14, it abuts against the overlying Virginia slate and has metamorphosed both the slate and the iron formation in this area.[a]

In general through the western and central portions of the Mesabi district the iron oxide of the iron formation is mainly hydrated hematite, and magnetite is in subordinate quantity. Eastward from Mesaba station the iron oxide is mainly magnetite, and hematite is in subordinate quantity. Westward from Mountain Iron the amphiboles are almost entirely lacking; from Mountain Iron eastward to Mesaba station the amphiboles are present in the iron formation, but are not abundant until Mesaba station is approached; eastward from Mesaba station they become abundant and make up an important constituent of the formation. In the eastern portion of the range the chert is correspondingly less abundant than in the western and central portions of the district, and in some cases is almost entirely absent. The chert becomes also distinctly coarser in this area. In range 12 the grains commonly reach a diameter of 3 or 4 millimeters, and there are a few smaller particles, while in the central and western portions of the district they are seldom greater than 0.10 millimeter, and almost invariably are associated with smaller particles (compare Pls. XV and XVII). Toward the east there is a tendency for the texture to become more

[a] The metamorphism of the Biwabik formation by the gabbro in the area adjacent to Birch Lake and eastward in the vicinity of Akeley and Gunflint lakes has been described in detail by U. S. Grant and W. S. Bayley, and has been briefly considered or mentioned by N. H. Winchell, H. V. Winchell, A. H. Elftman, J. E. Spurr, J. Morgan Clements, C. R. Van Hise, and others, as noted in the review of literature in Chapter II.

The intrusion of the granite and its metamorphic effect on the iron formation is here for the first time described.

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even, although there are many wide variations from uniformity. The chert grains, instead of being in irregular, roundish, and scalloped cherty forms, as in the central and western portions of the district, are in roughly polygonal shapes and united in a fairly uniform mosaic (Pl. XVII). Accompanying these changes is a more pronounced segregation of the magnetite and the amphibolitic chert into irregular layers and lenses, with the result that the iron oxide layers, instead of containing various other minerals, are comparatively free from them. The characteristic granules of the ferruginous cherts are still conspicuous in the east end of the district but in the most highly metamorphosed phases of the rocks, as in range 12, they have

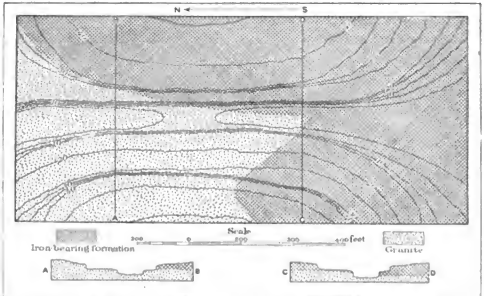

FIG. 5.—Sketch showing relations of Embarrass granite to the Biwabik formation in the abandoned glacial gorge in NW. ¼ of NW. ¼ of sec. 17, T. 60 N., R. 12 W.

entirely disappeared, being obscured by magnetite, amphibole, and chert In the phases not showing the maximum alteration they are marked by magnetite, either as a rim about the granule, as a solid mass filling it, or in evenly disseminated particles through it. Not infrequently the granules may be observed only in ordinary light and then by distribution of the magnetitic particles; in parallel polarized light they are obscured by the polarization of the amphibolitic and cherty constituents. Finally, in the eastern portion of the district certain minerals have developed which have not been found in the less altered rocks of the central and western portions

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of the Mesabi district. In the latter areas the amphiboles are entirely grünerite and actinolite, with little or no hornblende. In the eastern portion of the district the amphiboles include grünerite and actinolite, and in addition green and brown hornblende in considerable quantity. Associated with these minerals are small quantities of biotite, glaucophane (45057), andalusite (45124), zoisite (45119), and garnet. Still farther to the east, in the neighborhood of Gunflint Lake, the continuation of the Biwabik formation has suffered metamorphism by the gabbro, and, according to Grant,[a] there has been an extensive development of hypersthene, augite, and olivine, in addition to, and sometimes replacing, the minerals above mentioned.

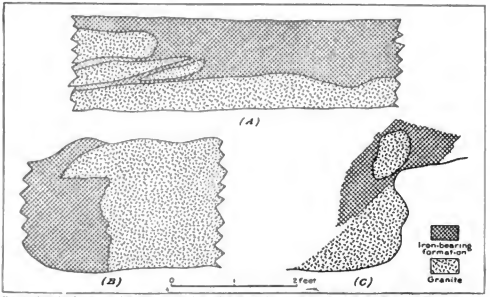

FIG. 6.—Details of contact of Embarrass granite and Biwabik formation in the gorge in NW. ¼ of NW. ¼ of sec. 17, T. 60 N., R. 12 W.

While hypersthene, augite, and olivine are abundant and characteristic in the true gabbro of range 12 and westward, these minerals are nearly, if not quite, lacking in the Biwabik formation.

Although eastward toward Gunflint Lake the gabbro alone has been able to produce even greater metamorphic effects on the iron-bearing rocks, it is certain that the metamorphism of the iron-bearing rocks in the region under description has been produced jointly by the gabbro and granite.

[a] See Chapter II.

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At the contacts of the iron formation with each of these rocks, detailed evidence of their metamorphic effects may be observed. For the gabbro contact the general description of the metamorphism above given applies almost in toto, the only exception being the statements concerning the augite, biotite, and andalusite, which are not found near the gabbro contact.

The granites, before this work was taken up, had not been known to be intrusive in the iron formation, and hence a brief detailed description of its contact effects may be of interest.

The contact effects of the granite may be well studied in the gorge in the NW. ¼ of NW ¼ of sec. 17, T. 60 N., R 12 W., where on both sides of the gorge are actual contacts of the rocks. (See figs. 5 and 6, and description of structural relations, pp. 187–188.) The iron formation is a very dark-gray and grayish-yellow ferruginous chert, highly siliceous, containing near its base a few undoubted well-rounded, fragmental quartz grains. The chert does not contain iron oxide in bands but in evenly disseminated particles and aggregates, in some layers in so small a quantity as to make the chert resemble a quartzite in general aspect. The only structure resembling a banding is a rough parting or jointing into thick, nearly horizontal, layers. The massive character of the rock here distinguishes it from the well-banded phases away from the contact.

At the top of the gorge, and down to within a few feet of the contact, the iron-formation rocks look siliceous and have disintegrated, brown, sugary surfaces where weathered. Under the microscope the quartz appears in medium-sized grains which have a tendency to be of uniform size for certain bands, although varying somewhat in different bands. The quartz grains are of polygonal shape and are fitted together in a fairly uniform mosaic No trace of clastic structure is to be observed, unless aggregation into indefinite bands be taken as evidence of sedimentary origin. Evenly disseminated through the quartzose background are particles and irregular aggregates of iron oxide, mainly magnetite, of green and brown hornblende, of actinolite or grünerite, of zoisite, and of biotite. In abundance the minerals stand in about the order named. The actinolite and grünerite are in minute, isolated, columnar forms and in radial and sheaf-like aggregates.

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Within a few feet of the contact the ferruginous chert shows a black, heavily ferruginous background, in which beautifully rounded quartz eyes are highly conspicuous because of their translucent character and their dark reflections. Under the microscope the grains appear well rounded and in some cases even show incipient enlargement. The matrix consists of greenish, transparent zoisite plates and dark, greenish-black aggregates of magnetite, zoisite, hornblende, grünerite, and actinolite (45119). The forms of the ellipsoidal granules are still to be observed in ordinary light by distribution of the iron oxide. Under crossed nicols the other minerals named completely obscure them. It is clear in connection with the alterations traced in the central part of the district that the rock was originally composed of ferrous silicate granules and of fragmental quartz grains in about equal abundance, and that the alteration of the ferrous silicate has given the dense, dark-green and black background in which the quartz grains now stand so conspicuously.

Immediately next to the contact with the granite, the quartz in the matrix of the ferruginous chert has been thoroughly recrystallized, considerably increased in size, and the round shape lost. The granite is rich in quartz which occurs as purple phenocrysts. Within a few inches of the contact almost identical quartz phenocrysts have been developed in the iron formation (see fig. *A*, Pl. XVIII), and in addition numerous irregular stringers and veins of quartz ramify through the iron formation. It looks as if there had been a minute injection of the quartz into the iron formation close to the contact through the agency of hot silica-bearing solutions accompanying the intrusion of the granite. Several specimens were collected, which consist of about one-half quartz in stringers and phenocrysts and about one-half iron-formation material. The contact of the iron formation and granite is ordinarily exceedingly sharp (see fig. *A*, Pl. XVIII) though in places an irregular gradation zone from an eighth of an inch to an inch thick separates the two. In this zone may be also observed pink feldspars and purplish quartz characteristic of the granite, lying in a black, ferruginous chert matrix, which, toward the granite side, fades out and toward the iron-formation side becomes more abundant until it excludes the feldspar of the granite. In this zone andalusite (45124) and biotite (45124), commonly associated, and glaucophane have been developed in small quantity, and the quantity of green hornblende, actinolite, and grünerite has been increased.

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COMPARISON OF THE METAMORPHIC EFFECTS OF THE GRANITE AND GABBRO.

The contact effects produced by the granite differ from those produced by the gabbro in the following ways:

(1) While there has been thorough recrystallization next to the granite contact, the size of the grains has not increased nearly so much as next to the gabbro contact.

(2) Accompanying the recrystallization next to the gabbro there has been a tendency toward the segregation of the magnetite into irregular masses and layers. It is possible to take out good-sized hand specimens of almost clear magnetite. Next to the granite contact it would be difficult to find magnetite well enough segregated to allow of this.

(3) Next to the granite contact there have been developed andalusite, zoisite, biotite, and glaucophane which are not characteristic of the gabbro contact in the area west of Birch Lake. On the other hand, green and brown hornblende are much less abundant than near the gabbro contact, and olivine and hypersthene, which in the Gunflint Lake area are characteristic of the gabbro contact (although not observed west of Birch Lake), are altogether lacking near the granite.

(4) The intrusion of the granite has caused the introduction of a considerable amount of quartz in stringers and phenocrysts into the iron formation adjacent to the contact. The gabbro has contributed little or no material to the iron formation in the contacts observed in the Mesabi district. To the east, near Akeley and Gunflint lakes, such transfer from the gabbro probably occurred.[a]

MAGNETIC ATTRACTION.

The normal magnetic variation for northeastern Minnesota where there is no local disturbance is 7° east of north. Throughout the Biwabik formation the needle shows deflections from this direction. In limited areas the deflections of the needle are most capricious, yet by putting together observations taken throughout the range it becomes apparent that there is some regularity in the magnetic attraction. In the eastern portion of the district a high and variable deflection can be counted upon, for here, as we have seen, there is much magnetite, due to the alteration of the Keweenawan

[a] See discussion of gabbro contact by Grant, Bayley, and others summarized in Chapter II.

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intrusives, and the drift covering is thin. Variations of 40° or 50° or even 90° are common. Through the central and western portions of the district the magnetic needle, on an average, varies but a few degrees from the normal, but so far as there is any variation it is greater in certain zones than in others. One of these is just within the iron formation near its contact with the Pokegama quartzite. It has a width varying from a few steps to a few hundred steps. In this zone variations as high as 30° to 40° are common. From this zone tongues of high attraction project to the south. Also in the neighborhood of some of the ore deposits a slightly higher attraction has been noted near the contact of the ore with the wall rock than in the rock or in the ore.

STRUCTURE.

The most conspicuous structure in the Biwabik formation is the bedding, which may be observed in all phases of the formation. The bedding layers may be several feet thick or as thin as those of shales. The more massive and irregular layers and the poorest parting are shown by the ferruginous chert, particularly the ferruginous chert in lower horizons of the formation. The finer bedding, accompanied by a better parting, is shown by the iron ores, by the slaty rocks within the iron formation, and by some of the ferruginous cherts in middle and upper horizons. The iron formation is a sedimentary formation interbedded with typical quartzite and slate, and the bedding as a whole is an original structure, but the formation has undergone such great metamorphism that the bedding has suffered many modifications. The iron formation originally consisted mainly of greenalite rocks with thin interbanded layers of slate. The alteration of the greenalite rocks to ferruginous chert has been accompanied by the segregation of the iron and silica into irregular bands and lenses which serve to mark the position of the original bedding, but at the same time obliterate much of it and make the parting parallel to the bedding very poor. The alteration of the greenalite rocks to the ore deposits has not obliterated any of the original bedding, but on the contrary has made it even more conspicuous and has made the parting parallel to it an excellent one.

The iron formation has been tilted gently away from the high land of the Giants range adjacent at an angle varying from 5° to 20°, but

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averaging perhaps 8° or 10°, and has, in addition, been gently flexed both parallel and transverse to the range. All of these features are indicated by the variation in direction and degree of dip in different parts of the formation, and may be actually observed on a small scale in the open cuts of the mines. Accompanying the folding is fracturing and even brecciation. The formation is cut by numerous joints, which in the massive cherty portions are even and continuous, but which in the fine bedded portions, and particularly in the ore deposits, are extremely irregular and for the most part coterminous with the individual layers. In some places, as at the Biwabik mine, and at the Hale and Kanawha mines, there is evidence that the faulting and brecciation of the iron formation has been greater near the contact of the iron formation with the underlying rocks than farther away from it. This is due to readjustment along the contact during the folding of the district.

Water flows easily through the formation parallel either to the bedding or to the joints. In the massive portions it probably is more nearly parallel to the joints than to the bedding, because of the poorer parting parallel to the latter. But in the more finely bedded portions the water could move in almost any direction.

Most of these structural features the iron formation shares with the other members of the Upper Huronian series, and are discussed more in detail in connection with the structure of the Upper Huronian series (pp. 178–180).

THICKNESS.

The thickness of the Biwabik formation has been directly measured in but one place, in sec. 34, T. 59 N., R. 14 W., where Mr. E. J. Longyear drilled from the Virginia slate through the iron formation into greenstone below, and found the iron formation to have a thickness of 576 feet. On the basis of average dips and width of exposure of the iron formation at any one place the thickness might be more than 2,000 feet or as little as 200 feet. Such great variation is in part real and in part apparent. The iron formation grades laterally into the Virginia slate (see pp. 172–176) and the formation was deposited against an irregular shore line and an irregular bottom of the Lower Huronian and Archean rocks, both causing variation in the real thickness of the formation. On the other hand the gentle foldings of the formation in two directions, coupled with the scarcity of dip

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observations, make the selection of a fair average dip across the formation at any given place an exceedingly difficult matter, and some of the apparent variation in thickness is unquestionably due to failure to take into account the minor folding. The average thickness for the district is perhaps in the neighborhood of 1,000 feet. The eastward continuation of the iron formation, near Gunflint Lake, has been estimated by Grant[a] to have a thickness of 825 feet.

RELATIONS TO OTHER FORMATIONS.

The Pokegama quartzite underlies the Biwabik formation for most of the district. The relations are those of a minor erosion interval. Structurally the two formations conform to each other; so far as can be ascertained, the dips of the Pokegama quartzite are identical with those of the overlying iron formation. The Pokegama quartzite had not been folded prior to the deposition of the iron formation, and, as members of the Upper Huronian series, both formations have been affected by the gentle Upper Huronian folding. However, at a considerable number of places in the district, and, it is believed, throughout the district, a layer of conglomerate a few inches to several feet in thickness separates the iron formation from the Pokegama quartzite. The pebbles in this conglomerate are in small part of quartzitic rocks like those underlying and show some variety, and hence the conglomerate must indicate the lapse of some time interval prior to its deposition. Yet, taken in connection with the thinness of the conglomerate, the characteristic scarcity of indurated quartzite fragments (see pp. 157–158), the comparatively small size of its fragments, and the correspondence in dip of the quartzite to the iron formation, it seems likely that the erosion interval represented by the conglomerate was not a great one.

The conglomerate is closely associated with a brecciated phase of the ferruginous chert, and in some places it is hard to draw a line between the two. The breccia indicates that in addition to the normal erosion unconformity there has been a slight amount of readjustment along the plane of contact between the quartzite and the iron formation, which probably occurred during the tilting and folding of the Upper Huronian strata. The Pokegama quartzite and the iron formation probably acted essentially as units during the deformation.

[a] Geol. Nat. Hist. Survey Minnesota, Final Report, Vol. IV, 1888, p. 486.

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For short intervals in the district the Pokegama quartzite has not been found between the Biwabik formation and the underlying rocks, and in such areas the iron formation rests unconformably on the Archean and Lower Huronian rocks.

Through much of ranges 12 and 13 the Biwabik formation lies directly upon intrusive granite, probably of Keweenawan age.

The Biwabik formation is overlain for the most of the district by the Virginia slate. In the eastern portion of the district evidence is not at hand to show the distribution of the Virginia slate, but presumably it is the rock immediately south and overlapping the iron formation until cut out by the overlapping of the Keweenawan gabbro. The Virginia slate and the Biwabik formation are perfectly conformable. The Biwabik formation throughout contains layers of slate which, near the upper horizons, become more numerous and finally form the Virginia slate. Moreover, the upper part of the iron formation grades laterally into slate, which has been mapped as the Virginia formation. The relations of the Virginia slate to the Biwabik formation are more fully discussed in connection with the Virginia slate.

Through much of ranges 12 and 13 the iron formation is overlain directly by the gabbro, and on the north side of Birch Lake the northeasternmost tongue of the iron formation is bounded both east and west by the gabbro.

SECTION III. VIRGINIA SLATE.

DISTRIBUTION.

The Virginia slate bounds the iron formation on the south from the west end of the district to near the east side of secs. 5 and 8, R. 13 W., where the slate is overlapped by the gabbro. Still farther east in the SW. ¼ sec. 25, T. 60 N., R. 13 W., drilling has shown altered slate to lie between Keweenawan gabbro on the south and Keweenawan diabase on the north, but whether it is an isolated mass at this point in the Keweenawan area, or is continuous with the slate to the west, explorations or exposures do not yet tell. The slate underlies the lower slopes of the Mesabi range and continues south under the low-lying swampy area south of the Mesabi range for an unknown distance. The area overlain by slate is so thickly covered with drift that exposures of the slate are almost entirely lacking; its presence and distribution have been determined by drilling and test pitting

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done in the search for iron. Through the central portion of the district enough of such work has been done to show the position of the slate boundary with a fair degree of accuracy, although even here there are considerable stretches where records of the occurrence of slate are wanting. In the western and eastern portions of the district the distribution of the slate is largely hypothetical, particularly so in the western end of the district. In drawing the slate line on the map of this portion of the area, all that can be done is to connect the widely separated explorations which reveal slate. Wherever exploration has been detailed it is found that the slate boundary is not straight, but in gentle curves, and it is reasonable to expect, therefore, that future work will show numerous additional undulations in the slate boundary for the area at present not completely explored.

KINDS OF ROCKS.

SLATE.

The normal Virginia slate is usually a gray rock, though in part black, reddish, or brown, with bedding shown by alternating bands of varying color and texture. Some of the beds are almost coarse enough to be called graywackes. Indeed, in the field the rock has been called a banded slate and graywacke. Some of the slate is hard and siliceous, while other phases, especially the nonsiliceous and carbonaceous ones, are soft and can be whittled with a knife. Near the contact of the slate with the iron deposit in the underlying iron formation, as at Biwabik and in sec. 3, T. 58 N., R. 15 W., the slate becomes iron stained and soft and grades into paint rock. The slate in general has a very poor parting parallel to bedding planes, and there is little or no development of secondary cleavage. What there is of secondary cleavage has been developed parallel to the bedding planes and is marked by minute particles of mica there found. While the rock in general aspect and mineralogic and chemical composition looks like slate, it differs from a true slate in lacking a true cleavage, and as this is one of the essential characteristics of slate, it may be doubtful whether the term slate ought to be applied to the rock. Yet the rock is not a shale, for it is too much metamorphosed and has too poor a parting parallel to the bedding. In the eastward continuation of the Mesabi district, east of Gunflint Lake, the same formation shows the characteristics of a true slate, and the formation both here and in the Mesabi district proper has been known

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locally and in geologic literature as slate. Hence the term is here retained.

Under the microscope the rock is seen to be a chloritic slate containing minute, more or less angular, pieces of quartz, and perhaps some of feldspar, associated with chlorite in confused aggregates. The chlorite makes up about half the rock. An occasional minute plate of mica is present with its greater diameter parallel to the bedding, possibly as a result of the incipient development of secondary cleavage. In general the grain, while exceedingly fine for some layers, is fairly coarse for a slate. The carbonaceous slates differ from the ordinary type only in containing minute specks of carbon tending to obscure the other constituents.

A partial analysis of the slate (specimen 45735), from south of the "Meadow" explorations in sec. 3, T. 58 N., R. 15 W., by H. N. Stokes, of the United States Geological Survey, is as follows:

Analysis of Virginia slate.

SiO_2	46.61
Al_2O_3	8.04
Fe_2O_3	25.77
Fe	18.04
MgO	2.82
CaO	.13
P_2O_5	.06
CO_2	None.

The following analysis by Mr. George Steiger, of the United States Geological Survey, is of a composite sample of the Virginia slate made up by assembling several specimens from two localities (specimen 45767 from excavation for water tank of Eastern Railway of Minnesota at Virginia; specimen 45463 from south of the Biwabik mine):

SiO_2	62.26
Al_2O_3	16.89
Fe_2O_3	1.76
FeO	4.55
MgO	2.05
CaO	.42
Na_2O	2.29
K_2O	3.02
H_2O-	0.70
H_2O+	3.88
TiO_2	.60
CO_2	None.
P_2O_5	.20
Organic undetermined	
	99.52

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LIMESTONE.

In the lower horizons of the Virginia slate, as well as in the upper horizons of the iron formation, is a considerable amount of limestone, interbedded with both slate and the iron formation. The rock effervesces readily with cold dilute hydrochloric acid, and hence probably does not contain much magnesia. The layers vary in thickness from several feet to a fraction of an inch. Near the horizon of the rapid transition of the slate into the iron formation there is a fairly persistent layer of the limestone several feet thick, although at many places it is lacking at this horizon. This may be well studied in the excavation at the water tank of the Eastern Railway of Minnesota at Virginia. The limestones are gray rocks, not to be discriminated by their color or texture from some of the coarser phases of the banded slates. Indeed, in some cases it was not until a test had been made with hydrochloric acid that the presence of carbonate was suspected. (Specimen 45464.) Under the microscope the calcite is observed in irregular grains and aggregates making up the bulk of the rock. Associated with the calcite are small quantities of quartz and chlorite in particles of about the same shape and size as those seen in the slate above described.

CORDIERITE-HORNSTONE RESULTING FROM THE ALTERATION OF THE VIRGINIA SLATE BY THE GABBRO.

In approaching the gabbro, which overlaps the Virginia slate in ranges 14 and 13, the slate becomes more crystalline, harder, and characteristically breaks with a conchoidal fracture, and the color becomes darker and frequently is a bluish black. The rock, indeed, becomes a hornstone. Moreover, there appear minute, light-colored specks which on the weathered surface are likely to have disappeared and to be represented by pits. Under the microscope the white specks are found to be cordierite in typical development, standing as numerous phenocrysts in a fine-grained matrix of biotite, feldspar, magnetite, and certain doubtful microlites which may be actinolite or sillimanite, or both.[a] (Figs. *B* and *C* of Pl. XIX.) The cordierite crystals appear in short, columnar forms or with hexagonal outlines, depending upon their position with reference to the plane of the slide. Their average diameter is between 0.10 and 0.20 millimeter, and

[a] Cordierite in this formation was first noted and described by N. H. Winchell, Geol. Nat. Hist. Survey Minnesota, Final Rept., Vol. V, 1900.

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their length varies from 0.40 to 0.80 millimeter. The single and double refractions are low and strikingly similar to those of quartz. Their distinguishing feature is the twinning, which in basal or hexagonal sections causes the crystals to lighten and darken in alternating sextants in revolving under crossed nicols. The cordierite crystals are more or less obscured by minute blades of biotite, and perhaps other micas, and by numerous columnar microlites of some greenish-white mineral, without pleochroism and with high single and low double refraction, whose character because of their small size is doubtful. They may be sillimanite, one of the characteristic associates of cordierite. Both macroscopically and microscopically the metamorphosed slate is *cordierite-hornstone*, as this term is used by petrographers such as Rosenbusch, Zirkel, and Harker.

A partial analysis of the cordierite hornstone (specimen 45699), from near the southeast corner of the NE. ¼ of SE. ¼ sec. 21, T. 59 N., R. 14 W., by H. N. Stokes, of the United States Geological Survey, is as follows:

Analysis of cordierite-hornstone.

SiO_2	70.48
Al_2O_3	12.46
Fe_2O_3	4.94
MgO	2.04
CaO	.71
P_2O_5	.11
CO_2	None.

From the Crystal Falls district, south of Lake Superior, Clements[a] has described and figured a spilosite which shows a most remarkable similarity to the cordierite-hornstone here described The porphyritic crystals and the background have the same general aspect, but when examined closely the phenocrysts in the rock described by Clements are found to be albite instead of cordierite.

RELATIONS OF THE VIRGINIA SLATE TO THE BIWABIK FORMATION.

Reference has already been made to the fact that the relations of the Virginia slate to the underlying Biwabik formation are those of gradation, both lateral and vertical. It remains to discuss this gradation somewhat fully. The iron formation contains slate layers throughout. In upper and middle horizons they are perhaps more numerous than in lower hori-

[a] The Crystal Falls iron-bearing district of Michigan, by J. Morgan Clements: Mon. U. S. Geol. Survey Vol. XXXVI, 1899, pp. 206–207, Pl. XXXVI.

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PLATE XIX

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PLATE XIX.

PHOTOMICROGRAPHS SHOWING METAMORPHISM OF VIRGINIA SLATE INTO CORDIERITE-HORNSTONE IN APPROACHING DULUTH (GREAT) GABBRO.

FIG. *A*.—Slate. Specimen 45463, slide 15736. From water tank of Eastern Railway of Minnesota, Virginia. With analyzer, x 70. This is the normal fine-grained Virginia slate, consisting of quartz and feldspar, chlorite, muscovite, biotite, and iron oxide, all of the constituents arranged with their longer diameters roughly parallel, though the chlorite and iron oxide are arranged to a less extent than the other constituents. Described, pp. 169–170.

FIG. *B*.—Same, without analyzer.

FIG. *C*.—Cordierite-hornstone. Specimen 45235, slide 15679. From near east quarter post of sec. 27, T. 59 N., R. 14 W. Without analyzer, x 70. This rock results from the alteration of the normal Virginia slate by the contact of the Duluth gabbro. The light round and oval spots are cordierite, which in ordinary light can scarcely be distinguished from quartz or feldspar. The matrix is the fine-grained one normal to the slate. Described, pp. 171–172.

FIG. *D*.—The same, with analyzer, x 70. The cordierite crystals may be distinguished by the trillings faintly shown on the round basal sections. As in ordinary light the cordierite resembles albite and quartz. In general aspect the cordierite-hornstone here described corresponds almost exactly to the spilosite of the Crystal Falls district described by Clements and to the feldspathic graywacke of the Penokee-Gogebic district, described by Van Hise. In both of these cases, however, the phenocrysts are albite instead of cordierite. Described, pp. 171–172.

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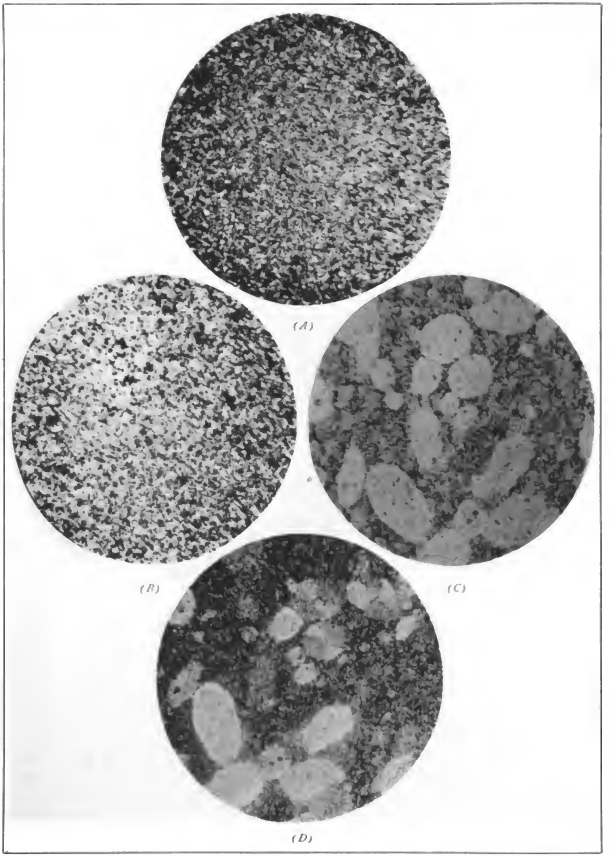

PHOTOMICROGRAPHS SHOWING METAMORPHISM OF VIRGINIA SLATE INTO CORDIERITE HORNFELS IN APPROACHING GREAT GABBRO FORMATION.

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zons. Just below the solid, black Virginia slate there is a zone in which there are many interlaminations of iron formation and slate, the layers varying in thickness from several feet to a fraction of an inch. This zone is of varying and uncertain thickness. In many places at least the zone of minute interbanding is thin, not more than 15 or 20 feet, but, as already noted, layers of slate are found well down in the iron formation, and layers of iron formation are found well up in the slate, so that in a broad way the gradation zone may be several hundred feet.

An examination of the map will show the Virginia slate to encroach on the south margin of the iron formation to greatly varying distances, with a result that the surface outcrop of the iron formation ranges in width from 2 or more miles to less than a quarter of a mile.

This might be explained by steeper dips at the narrow places than at the wide places in the iron formation, erosion having thus uncovered less of the iron formation where the dips were steep. This is probably a partial explanation of the narrowness of the iron formation belt in the neighborhood of Biwabik. The dips are on an average somewhat greater at Biwabik than at Mountain Iron, for instance. However, the difference in dip is not sufficient to account for the extreme narrowness of the formation near Biwabik, nor in the area as a whole is there uniform variation of the dip sufficient to account for variation in width of the formation.

The distribution might be explained by the greater dip of the plane of surface erosion, either atmospheric or glacial, in places where the formation is wide than where narrow, the greater dip of the surface bringing it more nearly parallel with the dip of the iron formation and thus uncovering more of it. While this may help to explain the distribution, the dip of the the plane of erosion does not show the requisite variation in inclination to fully account for the observed distribution.

Finally the distribution may be explained by the lateral gradation of the iron formation into the Virginia slate. This is believed to be the principal cause of the present distribution. In the Biwabik area, where the slates encroach on the southern boundary of the iron formation, the lack of sufficient steepness in dip of strata or flatness of plane of erosion leaves the lateral gradation of the iron formation into slate as the only alternative explanation of the distribution at this point. Moreover, in following the iron formation eastward from the Biwabik mine through the Cincinnati

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property the iron formation and slate are actually found interbedded directly along the strike of the iron formation. At numerous points in the district, as already noted, the iron formation becomes interstratified with slate toward its upper portion. This being the case it would be strange indeed if the conditions favorable to the deposition of slate had been reached at exactly the same time all over the range. Indeed, it would be more reasonable to suppose that while at some places the iron formation alone was being deposited, at other places iron formation and slaty layers were being alternately deposited, and at still other places slate alone was being deposited, thus giving a lateral gradation from iron formation into slate.

COMPARISON OF SLATE OF VIRGINIA AND BIWABIK FORMATIONS.

It is difficult to discriminate the Virginia slate from slate layers in the iron formation on lithologic, chemical, or textural grounds, for each of these slates has a variety of phases and some of them are common to both. But while in an individual case it may not be possible satisfactorily to discriminate between the two, in general, the differences are believed to be somewhat as follows:

(1) The Virginia slate has a predominance of grayish tones, while the slates interstratified with the iron formation have red, brown, or black tones.

(2) The slate in the iron formation is probably more frequently broken into small parallelopiped blocks, or is more likely so to part, than the Virginia slate. Insufficient observations have been made to warrant positive statements, but in this opinion the writer is in agreement with some of the leading mining engineers on the range.

(3) The slates in the iron formation contain abundant grünerite, while the Virginia slate contains almost none of it.

(4) The slate in the iron formation contains on an average a lower percentage of alumina, a higher percentage of iron, and in some cases a higher percentage of silica than the Virginia slate.

In the mapping, where pits or drill holes have shown slate of considerable thickness with few or no iron-formation layers in it, it has been mapped as Virginia slate. Where the slate is mixed with the iron-formation layers in considerable quantity, or the iron-formation material has been found to the south of it, the slate has been included in the iron formation. (See p. 148.)

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STRUCTURE.

Opportunities for studying the structure of the Virginia slate in situ are so few that if the observer were dependent upon such observations alone he would be unable to make any statements concerning the structure of the formation beyond the fact that it dips at low angles away from the high land adjacent. However, the slate is a conformable part of the Upper Huronian series, the other members of which show clear evidence of folding and fracturing. The Virginia slate must have partaken in this deformation. The statements applied to the structure of the Upper Huronian series on pp. 178–180 will therefore apply to the Virginia slate, but with one modification. Drill holes going through slate into iron formation sometimes reach water under pressure, indicating that the water has been ponded in the iron formation under the slate. This indicates the relatively pervious character of the iron formation, and it seems likely that in the gentle folding of the Upper Huronian series the brittle iron formation was more broken than the soft slate and thus affords freer passage to water than the slate.

THICKNESS.

The thickness of the Virginia slate can not be determined in the Mesabi district. The drift covering is thick, mining exploration stops to the south where the slates are encountered, and the southerly extent of the slate belt is thus unknown. To the south of the range, however, there is a low, swampy area, west of the gabbro, extending southward for about 35 miles at its widest, which is presumably underlain by slate. If the slate occupies all of this area, it must have a vast thickness. In the neighborhood of Gunflint Lake and eastward the equivalents of the Virginia slate and their upward extension have been estimated by Grant[a] to have a thickness of 2,600 feet. This does not represent the total thickness of the formation, but simply the part not covered by the gabbro. In the Penokee-Gogebic district the Upper Huronian slate lying above the iron formation has a present maximum thickness of 13,000 feet.[b] Thus the Virginia slate, which has an inconsiderable thickness in the district covered by the general map of the Mesabi range, is continuous with a formation extending to the south which probably has a great thickness.

[a] Geol. Nat. Hist. Survey Minnesota, Final Rept., Vol. IV, p. 486.
[b] Mon. U. S. Geol. Survey Vol. XIX, p. 456.

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SECTION IV. STRUCTURE OF THE UPPER HURONIAN SERIES.

As a whole the Upper Huronian is a well-bedded series of sediments. The bedding is most pronounced in the middle and upper horizons. The beds have gentle dips, averaging between 5° and 20°, though locally greater or less, in southerly and southeasterly directions away from the older rocks forming the core of the Giants range, but locally the dips show much variation both in degree and direction. About the southerly projecting tongue of the Giants range, in the vicinity of Virginia, Eveleth, and McKinley, the dips are westerly on the west side of the tongue, southerly at the end of the tongue, and southeasterly on the southeast side; that is, throughout approximately normal to its periphery. Even more conspicuous than the change of dip at such a place are the minor variations between exposures. Seldom is it possible to get two identical readings in dip at exposures of rock separated by even short intervals, although the direction and amount of the dip come within the above limits. These facts indicate that the beds of the Upper Huronian series are tilted away from the core of the Giants range in directions normal to its trend, and that the gently tilted beds are not plane surfaces, but are gently flexed. By tabulating and comparing the dips it becomes further apparent that the greater flexures are not random ones, but generally have their axes normal to the trend of the range. Examining the attitudes of the beds still more in detail, it appears that the great flexures themselves are not simple, but have many subordinate flexures, some of them transverse to the major ones. The complexity of the structure may be likened to that of water waves. On the great swells and troughs there are smaller waves, on the smaller waves there are still smaller ones, and so on down to the tiniest disturbance of the surface. While perhaps the majority of the minor flexures in the Upper Huronian rocks have attitudes similar to the larger ones, many of them vary greatly in direction. They may be observed at almost any single exposure of the Upper Huronian series.

While the great flexures are very gentle, involving very small changes in degree and direction of dip, the minor flexures superimposed upon the greater ones are frequently sharp and conspicuous. The local dips may vary as much as 50° within a few hundred feet and change their direction considerably. Dips as high as 45° or even 60° may be seen in the iron-formation layers in some of the open pits of the mines, as at the Stevenson,

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the Sauntry-Alpena, the Kanawha, and the Sparta. A series of dips taken at intervals through the Mountain Iron, Oliver, and Biwabik open cuts are tabulated in connection with the description of the ore deposits (pp. 225–226). The iron formation shows more minor contortion than the rest of the series, because of the great chemical changes which it has undergone, but it is not probable that there is any great difference in the major folding.

Accompanying the tilting and minor folding of the Upper Huronian series there has been a very considerable amount of fracturing, especially in the comparatively brittle Pokegama and Biwabik formations. Indeed, it seems likely that the folds of the two lower members of the Upper Huronian series are mainly the result of relatively small displacement along fractures, and only to a small degree the result of the actual bending of the strata without breaking. The ponding of water beneath the Virginia slate would seem to indicate that this formation has been less fractured than the iron formation because of its less brittle character, and had thus yielded to deformation by actual bending rather than by breaking. On almost every exposure of Pokegama and Biwabik formation rocks joints and minute faults are to be observed cutting almost perpendicularly across the bedding. In each case the joints seem to make up two or more systems crossing each other at various angles, but such sets have little constancy of direction in widely separated exposures, unless we except a set of joints which at a number of places have an average direction of somewhere between N. 60° and 70° E.—that is, approximately parallel to the trend of the range. In the massive rocks the joints are clear cut and continuous for considerable distances. In the well-bedded rocks, as, for instance, in the thin-bedded portions of the iron formation, the joints are usually more irregular, less continuous, and less conspicuous. In such places each individual bed may be more or less jointed without reference to the layers above or below.

The displacement or faulting along joints has been, in general, small. The displacement is rarely 3 or 4 feet, and commonly it is measured by a few inches. In the neighborhood of some of the iron deposits of the Biwabik formation certain facts doubtfully indicate a greater displacement, but this is discussed in connection with the ore deposits.

Certain of the joints and faults have been filled with vein quartz and others not. It is rather surprising that so little vein quartz is to be observed. Where present in the harder rocks, where the joints are clear cut and

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continuous, the quartz veins appear likewise. In the well-bedded portions of the iron-bearing formation, where the joints are irregular and discontinuous, the distribution of the vein quartz is also irregular and discontinuous, being rather in a confused zone than a well-defined plane.

After the Upper Huronian series were tilted and folded, the upper edges of the series were eroded away, with the result that the rock surface is now irregular, with dips corresponding roughly in direction, but not in degree, with those of the underlying rock strata, being, in general, less steep.

SECTION V. THICKNESS OF THE UPPER HURONIAN SERIES.

From what has been said concerning the thickness of the constituent members of the Upper Huronian series, it is apparent that accurate statements of the thickness of the Upper Huronian series as a whole are not possible. The Pokegama quartzite varies in thickness from 0 to 500 feet and averages perhaps 200 feet. The Biwabik iron formation ranges in thickness from 200 to 2,000 feet and averages perhaps 1,000 feet. The Virginia slate extends indefinitely southward beyond the limits of the area under investigation. Within the area studied an actual thickness of nearly 400 feet has been observed. Assembling these figures, it appears that the maximum figure for the thickness of the Upper Huronian series within the limits of the district mapped may be 3,000 feet, while the average may be 1,500 feet. But the total thickness of the Virginia formation, including its southward extension, is probably several times as great as the thickness of the two lower members of the series combined, for the thickness of the formation in this area may be commensurate with its thickness in the Penokee-Gogebic area, as the extent of the flat area south of the range would seem to indicate.

SECTION VI. RELATIONS OF THE UPPER HURONIAN SERIES TO OTHER SERIES.

The Upper Huronian series lies unconformably upon the Archean and Lower Huronian rocks. The proof of unconformity is as follows:

(1) The conglomerates at the base of the series (listed under the discussion of the Pokegama quartzite) contain fragments derived from the underlying rocks.

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(2) There is discordance in dip. The underlying formations, where they have any parallel structure at all, are almost vertical. The Upper Huronian is well bedded, with a low dip. Moreover, in approaching the contact no change of dip is to be observed, either in the Upper Huronian or in the underlying rocks.

(3) There is a difference in the amount of minor folding, fracturing, secondary cleavage, and further consequent metamorphism of the two series, the Upper Huronian being much less affected than the older series.

(4) The Upper Huronian belt overlies Archean and Lower Huronian rocks indiscriminately. Near Biwabik, for instance, the northern edge of the Upper Huronian series lies diagonally across the contact of the Archean and Lower Huronian rocks.

(5) The Lower Huronian is intruded by the granite making up much of the core of the Giants range. The Upper Huronian series is not so intruded, and, moreover, in the conglomerate at its base it bears fragments of this granite.

The Upper Huronian series, in ranges 12 and 13, is in eruptive contact with the Keweenawan granite and gabbro, as fully shown in the section devoted to the Keweenawan.

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CHAPTER VI.

KEWEENAWAN, CRETACEOUS, AND PLEISTOCENE ROCKS.

SECTION I. THE KEWEENAWAN ROCKS.

DULUTH GABBRO.

A portion of the great mass of Keweenawan gabbro of northern Minnesota comes within the limits of the Mesabi district. The northern edge of the mass lies diagonally across the eastern end of the district, extending from near the Duluth and Iron Range track, in range 14, northeasterly through ranges 13 and 12 to Birch Lake. Through range 14 the gabbro is in contact with Virginia slate; in ranges 13 and 12 it is in contact with the Biwabik iron formation, and north of Birch Lake it is in contact with Lower Huronian granite. The northern edge of the gabbro forms a conspicuous northward-facing escarpment overlooking the low-lying area of the Virginia slate and of iron formation immediately to the north. To this the name Mesabi range was first applied. In the neighborhood of Birch Lake the gabbro comes well up on the crest of the Giants range, and here it does not stand above the adjacent rocks.

The gabbro exposures show a parting into massive bands usually 10 to 20 feet thick, but sometimes ranging down to a few inches. As certain layers have somewhat different textures from those above and below, it is certain that the structure is at least in part one induced in the gabbro when it first cooled, but also a considerable amount of the parting may be a secondary phenomenon. The banding of the gabbro in the Mesabi district may be well observed near Allen Junction, where it dips to the northeast at an angle of about 40°. In addition to the parting into bands the gabbro is cut by vertical joints. Occasionally a combination of the joints and banding structures causes the rock to weather into spheroidal blocks, which at first glance look surprisingly like conglomeratic bowlders. This feature

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also may be observed in the gabbro about three-quarters of a mile north of Allen Junction.

The petrography of the gabbro of northeastern Minnesota has been exhaustively described by Irving,[a] Bayley,[b] Winchell,[c] Grant,[d] Elftman,[e] Clements,[f] and others, and the part which comes within the Mesabi district shows no features not covered in these descriptions. In characterizing the gabbro in the Mesabi district one can not do better than to quote a brief summary of the petrographic character of the gabbro as a whole by Dr. U. S. Grant:

> The gabbro is a coarse-grained aggregate of plagioclase, which is near labradorite; augite, which is often diallagic; olivine and magnetite, with occasionally hypersthene, biotite, hornblende, and minor accessory minerals. In general, the mass is of fairly uniform composition. Variations, however, take place mainly in three directions: First, by increase of feldspar the rock becomes an anorthosite; second, by increase of feldspar and olivine a forellenstein is formed; third, by increase of magnetite masses of titaniferous magnetic iron ore originate. Along its northern limit the gabbro, while at times assuming a finer grain, usually preserves its coarse grain and granular texture to its contact with the underlying rocks.[g]

The gabbro mass has been generally regarded as an extrusion forming the base of the Keweenawan, but recent work on the relations of the gabbro to adjacent formations, especially near Gunflint and Akeley lakes, has led Van Hise, Clements, Grant, and the writer to the belief that the gabbro is a laccolitic intrusion.

CONTACT PHASES OF GABBRO.

On the north side of Birch Lake the gabbro, where in contact with the iron formation, shows a segregation of coarse magnetite octahedra in layers. Moreover, at this point biotite and the orthorhombic pyroxenes, particularly enstatite and hypersthene, become more abundant, while the monoclinic pyroxenes are correspondingly less abundant. These features are common to the gabbro contact in other parts of northern Minnesota.

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[a] Mon. U. S. Geol. Survey Vol. V, 1883.

[b] Jour. Geol., Vol. I, 1893, pp. 433–456, 587–606, 688–716; Vol. II, 1894, pp. 814–825; Vol. III, 1895, pp. 1–20.

[c] Reports of Geol. Nat. Hist. Survey Minnesota, latest conclusion in Final Rept., Vols. IV and V.

[d] Engineers Yearbook, Univ. of Minn., 1898, pp. 49–62. Bull. Geol. Soc. Am., Vol. XI, 1900, pp. 503–510; also in Reports of Minn. Surv. (see Chapter II).

[e] Am. Geol., Vol. XXI, 1898, pp. 90–109, 175–188, contains full bibliography; Vol. XXII, 1898, pp. 131–149.

[f] Mon. U. S. Geol. Survey Vol. XLV.

[g] Contact metamorphism of a basic igneous rock, by U. S. Grant; Bull. Geol. Soc. Am., Vol. XI, 1900, pp. 503–505.

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North of Birch Lake also (see fig. 7) is a curious contact rock between the gabbro and Lower Huronian granite. Between the coarse gabbro and the normal coarse granite is a narrow zone, perhaps 150 feet wide, occupied by a fine-grained micaceous rock, varying from brown to pink in color, which looks in places like a fine-grained gabbro and in others like a fine-grained granite. In the field it was not determined whether the rock was an altered gabbro, an altered granite, or an intermixture of the two, and microscopic study does not help us out much. The rock is

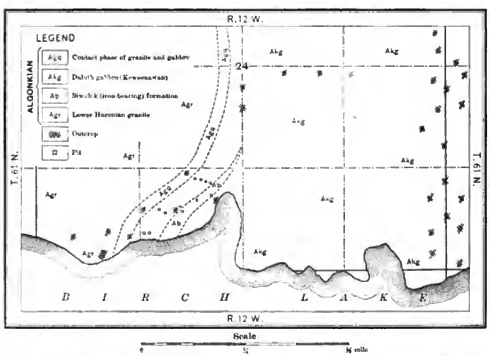

FIG. 7.—Detail map showing distribution of Lower Huronian granite, Biwabik formation, Duluth gabbro, and contact phase of granite with gabbro on the north shore of Birch Lake.

composed mainly of feldspar, largely orthoclase, although so obscured by cloudy alteration as to make accurate determination difficult, biotite, and quartz. The texture is granitic. These are features characteristic of granite, and, whatever the rock once was, it should probably now be called a granite. However, it is still possible that the rock represents a fine-grained contact phase of the gabbro for the reasons that (1) the character of the feldspar is doubtful, (2) biotite is one of the characteristic minerals developed in the gabbro near its contact, (3) in the area eastward toward

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Gunflint Lake free quartz has been found in the gabbro itself, and (4) in this eastern area also the exomorphic effects of the gabbro contact on the granite are very slight.

DIABASE.

There are in the Mesabi district certain rocks associated with gabbro which are not covered in the above general account. In range 13 exposures of fine-grained diabase appear in the SW. ¼ sec. 25, T. 60 N., R. 13 W., and in the central and northern portions of sec. 35, T. 60 N., R. 13 W. Bowlders of the same material indicate its extension for several miles east and west, and, taken together with the exposures, indicate a belt with a possible width of something less than a mile, a length of at least 3 miles, and probably much more, and a trend northeast and southwest—that is, parallel to the general strike of the formation boundaries in this part of the district. The diabase is a fine-grained dark-gray rock which, under the microscope, shows a well-developed ophitic arrangement of plagioclase feldspar crystals and the presence of abundant hornblende and less abundant ilmenite and magnetite. The diabase corresponds lithologically to the diabase sills intruded in the iron formation in the neighborhood of Gunflint Lake, and there supposed to be either offshoots of the gabbro or intrusives both in the gabbro and adjacent rocks. The trend of recent opinion is toward the former conclusion. In the SW. ¼ sec. 25, T. 60 N., R. 13 W., south of the diabase, drill holes have recently penetrated altered slate (cordierite-hornstone). The relations of the slate to the surrounding rocks are unknown because of lack of exposures and exploration. If the slate is continuous with that to the west, which had not heretofore been known to extend farther east than sections 5 and 8 of the same range, the diabase must be a sill intruded in the Upper Huronian series. If the slate is not continuous with the main belt of slate to the west it must be an isolated mass in the Keweenawan rocks, and the diabase would belong with the main mass of the Keweenawan. From the analogy of its lithologic character with that of the diabase sills to the east, from its distribution, and from the occurrence of slate to the south, it is thought that the diabase is probably a sill, but lack of exposures and sufficient exploration make it quite impossible at present to show its boundaries on the map. The area to the south of the diabase, including that in which the slate has been found, is therefore mapped as Keweenawan.

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A little southeast of the northwest corner of sec. 34, T. 59 N., R. 14 W., Mr. E. J. Longyear found diabase in a drill hole at the depth of 984 feet, having passed through 16 feet of drift, 392 feet of black slate, and 576 feet of iron formation. Three hundred and nine feet of diabase were penetrated before the work was stopped. The iron formation is bounded on the north by Lower Huronian graywackes and slates, upon the eroded edges of which lies the iron formation, with perhaps a thin layer of Pokegama quartzite between. The fact that the diabase, rather than the Pokegama quartzite or Lower Huronian graywacke and slate, was reached by the drill below the iron formation would be in accord with the supposition that the diabase formed a sill intruded into the iron formation at this place.

EMBARRASS GRANITE.

Through ranges 12 and 13, and as far west as sec. 2 in range 14, a distance of 15 miles, the granite forming the core of the Giants range is intrusive into the Upper Huronian series. Whether it was intruded at the close of the Upper Huronian epoch or during the succeeding Keweenawan is a matter of doubt, and indeed is a matter of small consequence. The fact that granite dikes cut the Keweenawan series in other parts of northern Minnesota makes it a plausible assumption that the granite was intruded in Keweenawan time, but no relations of the granite to the Keweenawan have been observed in the Mesabi district. The granite is named the Embarrass granite from its lithologic similarity to granite exposed at Embarrass station on the Duluth and Iron Range Railroad, just north of the Mesabi range.

The Embarrass granite is a pink hornblende-granite. It is usually of coarse grain, but shows much variation. In general the grain becomes finer toward the west. The characteristic feature of the granite is its large content of quartz in small and large grains, which are very conspicuous, especially on the weathered surface. The quartzes range in diameter from over a centimeter to a few millimeters. When large they have a characteristic purplish-blue color. In its content of quartz the Embarrass granite is readily distinguished from the Lower Huronian granite in the central and western parts of the range, in which the quartz is exceedingly rare or entirely lacking. Other constituents are pink orthoclase feldspar, which sometimes occurs as prophyritic crystals almost an inch long, and a rather small amount of hornblende. The relative abundance and coarseness

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of all the constituents of the granite of course show the usual variations of a large granitic mass.

Under the microscope the feldspar is observed to be orthoclase, rarely microcline. Usually it is fresh, but where weathered shows cloudy alterations to kaolin and mica. Zonal growths of the feldspar grains are conspicuous features. The hornblende is of the common green variety. The quartz for the most part is clear and limpid, but shows undulatory extinction and minute inclusions in irregular aggregates and in lines. In addition to the essential constituents there is present a considerable quantity of sphene, and some black oxide, which from its common association with sphene is taken to be ilmenite rather than magnetite. An occasional crystal of andalusite, and perhaps also tourmaline and garnet, are to be observed (specimens 45075 and 45139).

Cutting the granite are a few dikes of finer-grained, lighter-colored quartzose granite, which under the microscope is found to differ from the one just described only in lacking hornblende and the rare elements mentioned.

PROOF OF INTRUSION OF EMBARRASS GRANITE INTO THE UPPER HURONIAN SERIES.

Through the central and western portions of the Mesabi district there is abundant evidence that the Giants Range granite is older than the Upper Huronian rocks, and it has always been assumed that this conclusion applied to the eastern portion of the range as well. The first conclusive proof that the granite of the eastern portion of the range is intrusive into the Upper Huronian series, instead of older than it, was found in a gorge in the NW. ¼ of NW. ¼ sec. 17, T. 60 N., R. 12 W., where the contact between the granite and the iron formation is well exposed. Figs. 6 and 7 show the relations of the two formations. The proof of intrusive relations at this point may be briefly summarized as follows:

(1) There are knife-edge contacts or occasionally a gradation zone a fraction of an inch in thickness, as shown by fig. *A* of Pl. XVIII.

(2) At these contacts there is no trace whatever of any conglomeratic material derived from the granite.

(3) The lower part of the iron formation is penetrated by granite dikes, and irregular layers of iron formation are found partly sliced off by the granite (see fig. 6). At one place a mass of the granite cuts across the stratification of the iron formation for a distance of 5 feet vertically, and

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the upward continuation of the granite at this point appears as a dike in the upper surface of the iron formation. The stratification of the iron formation has suffered a little disturbance, for it dips north rather than south in this immediate vicinity.

(4) The iron formation in contact with the granite has undergone considerable metamorphism, as described on pages 161–163.

(5) At the contact there has been in places an abundant separation of quartz along the periphery of the intrusive granite or between the layers of the iron formation.

The intrusion of the granite is shown by the relations observed in the gorge above described and by drill records to have been mainly parallel to the stratification of the iron formation, which lies with a very gentle dip to the south, but in a minor way the granite has broken across the stratification. The granite is coarsely crystalline, and must have cooled far below the surface, when the iron formation was deeply buried.

After the intrusive relations of the granite and Upper Huronian had been worked out in the gorge above described and the peculiar quartzose character of the granite noted, the granite of the Giants range both east and west was reexamined to see how much of it is of this character and how much older granite. The newer granite was found to continue eastward as far as Birch Lake and westward to sec. 2, T. 59 N., R. 14 W., where it stops abruptly. From here westward the granite is of the normal Lower Huronian type.

At Birch Lake the Embarrass granite and Lower Huronian granite are well exposed along the shores, and their relations may be satisfactorily studied. The older granite occupies much of the north shore and extends widely northward to White Iron Lake and beyond. It is identical in character with the Giants Range granite through the central and western portion of the Mesabi district, though if anything it is a little coarser. Cutting this granite are younger quartzose granites of at least two periods of intrusion, one of them, the finer grained, being often in north and south trending dikes in the other. The coarser quartzose granite is perhaps the counterpart of the main mass of Embarrass granite above described, and the finer and lighter quartzose granite corresponds to the dikes in the Embarrass granite; but whether or not this correspondence holds, the quartzose granite in general is clearly a part of the Embarrass granite to the southwest, and is intrusive into the older or Lower Huronian granite, as would be expected.

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SECTION II. CRETACEOUS ROCKS.

In a number of places in the central and western portions of the Mesabi district there are small, thin, isolated patches of Upper Cretaceous sediments resting unconformably upon the Upper Huronian formations. By referring to the map such areas may be noted near Virginia, Mountain Iron, Buhl, in secs. 13 and 24, T. 56 N., R. 24 W., and in sec. 31, T. 57 N., R. 22 W. Certain deposits of blue clay in various parts of the range, well shown on the high hill in secs. 22 and 23, T. 55 N., R. 26 W., may also be of Cretaceous age. At the Oliver mine a small patch of conglomerate may be found resting on the ore. The Cretaceous rocks must have much wider distribution than this, but thus far exploration has not shown them. However, while they probably occupy a much larger area than is indicated on the map, they do not, by any means, cover all of the area, as is shown by the numerous explorations passing directly from drift into the Upper Huronian formations. From the distribution of the few remnants now known it is certain that Cretaceous rocks once overlaid all of the district west of range 16, that they may have extended further to the east, and that erosion has largely removed them from the area they did occupy.

The rocks consist of conglomerate and shale. The conglomerate, in the occurrences known, overlies iron formation and sometimes iron ore. As would be expected, therefore, the fragments of the conglomerate are derived from the iron formation. They consist mainly of heavy ferruginous chert and iron ore, both hematite and limonite. Except locally, and especially when the pebbles are of hard material, they are not well rounded. There are present in the conglomerate also fossils which are described below. The fragments are but loosely cemented. When broken out of the ledge the rock is fairly compact, but on being exposed to weathering it soon disintegrates. The cement is largely ferruginous, but there is present also a considerable amount of white or yellow substance which Mr. A. T. Gordon, chemist of the Mountain Iron mine, found to consist of silica and alumina, and it is thus essentially a clay. Occasionally there may be observed also minute greenish-yellow particles in the cement which may be glauconite grains, so common to the Cretaceous.

The shales are soft, thin-bedded rocks of a bluish-gray color when fresh, but frequently of a light color due to bleaching. These, too, contain fossils.

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FOSSILS.

Selected specimens of the shale and conglomerate containing fossils were submitted to Mr. T. W. Stanton, paleontologist of the U. S. Geological Survey, for examination. He pronounced them to be "unquestionably Upper Cretaceous forms—not older than the Fort Benton, and probably not younger than the Fort Pierre" horizon. Mr. Stanton's report is as follows:

The specimens have four different lot numbers, three of which Mr. Leith informs me refer to one locality, "Arcturus mine, in sec. 24, T. 56 N., R. 24 W., Mesabi iron range, Minnesota." These are all fossiliferous. The specimens numbered 45510 are similar lithologically, but show no recognizable fossils, and will not be again referred to.

The forms recognized in each lot are as follows:

No. 45573. *Mactra* sp. A small form closely resembling *M. gracilis* Meek and Hayden, but probably distinct species. *Inoceramus* sp. An immature specimen that may be young of *I. fragilis* Hall and Meek.

No. 45576. *Mactra* sp. Same as above. *Lunatia* sp. A single small cast.

No. 45733. *Ostrea* sp. One or possibly two small species of oysters not specifically identifiable with any described form from the western interior. *Inoceramus* sp. A fragmentary small specimen like the one in No. 45573. *Mactra* sp. Same form as in the other lots. *Cardium* sp. Fragmentary imprint of the surface of a costate shell probably belonging to this genus.

These fossils are unquestionably marine Upper Cretaceous forms, but the exact horizon represented by the bed yielding them has not been determined with certainty. The *Inoceramus* may be the young of *I. fragilis*, which is a Fort Benton species, while the other forms belong to types that may occur in any of the Cretaceous horizons above the Dakota. On the basis of the present evidence I can only say that the horizon is not older than the Fort Benton and probably not younger than the Fort Pierre.

In 1893 Mr. H. V. Winchell, of the Minnesota survey, submitted fossils from the same horizon to Dr. C. A. White, of the National Museum. Dr. White referred them to the Colorado formation of the Upper Cretaceous. His report is as follows:[a]

I have examined the small collection of fossils which you obtained from the Mesabi range in northern Minnesota, and, although they are all in an imperfect condition, I do not hesitate to refer them to the Upper Cretaceous. The following genera are represented by the collection: *Ostrea*, *Inoceramus*, *Modiola*, *Pinna*, *Yoldia?*, *Trigonarca*, *Actaeon?*, *Trochus?*, and *Fasciolaria*. A part of the species represented by the specimens constituting this collection are evidently new. Some described species are thus represented, and others are probably referable to described species, but they are too imperfect to admit of satisfactory determination.

[a] Am. Geol., Vol. XII, 1893, pp. 220-222.

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The *Yoldia?* referred to is much like the *Y. microdonata* of Meek and Hayden, reported to have come from the Dakota group of Kansas. The *Inoceramus* can not be distinguished from the *I. fragilis* of Hall and Meek. This is a characteristic species of the Colorado formation. For this reason, and because that formation is known to be represented at other localities in Minnesota, I think there is little, if any, reason to doubt that the deposit from which you obtained these fossils represents a portion of the Colorado formation as it is developed in the great interior part of the continent.

This discovery of a Cretaceous deposit at a point so far to the northeast in Minnesota is a matter of much geological interest, and, together with other similar discoveries in that State, leaves no room for doubt that the Cretaceous sea covered a large part, if not all, of its present area.

Later Mr. H. V. Winchell submitted other fossils from northern Minnesota, on which Dr. White reported as follows:

In addition to the *Inoceramus*, *Modiola*, and one or two others that were sent in the first lot from the same locality, there are several other forms, each represented by a single specimen, as follows:

1. *Placenticeras* (*Sphenodiscus*) sp. undet. (Collected by Samuel Sanford.) Part of the inner whorls of a form related to *P.* (*Sphenodiscus*) *lenticulare* Owen, from which it differs in having a broader umbilicus and more simple septa.

2. *Pholadomya* * * * Resembles *P. subventricosa* M. and H., though neither the type nor Mr. Winchell's specimen is well enough preserved to make the comparison satisfactory.

3. *Barbatia* * * * An imperfect cast.

4. A reptilian tooth.

In addition to the fossils above noted, the Cretaceous on the Mesabi has been found to contain small shreds of lignitic material. The presence of this material well up on the Mesabi range suggests the possibility of finding lignite deposits of commercial value in the low area to the west, north, or south of the Mesabi range.

SECTION III. PLEISTOCENE OR GLACIAL DEPOSITS.

The Mesabi district is covered by a mantle of glacial drift, of the late Wisconsin epoch, which effectually conceals the greater part of the Archean, Huronian, Keweenawan, and Cretaceous rocks above described. On lower slopes the drift is thick, sometimes reaching 150 to 200 feet, and here of course rock exposures are rare; on middle slopes the thickness commonly does not exceed 50 or 60 feet, and 20 to 50 would measure much of it; on the upper slopes of the range the drift is thin or altogether lacking and rock exposures correspondingly abundant. In the eastern portion of the district

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also, where the Giants Range granite has a higher elevation than to the west, the drift is thin and allows numerous rock masses to project through; toward the west, as the elevation of the Giants range decreases, the drift becomes thicker, until westward from Grand Rapids it buries even the crest of the Giants range to a depth of more than 100 feet.

Most of the drift in the Mesabi district may be classified as till. It consists of bowlders and clay, and in small part of gravel and sand, mingled indiscriminately. The bowlders are nearly all derived from the Archean and Huronian rocks, either immediately subjacent or from the Giants range to the north, although there is also a sparse sprinkling of bowlders derived from rocks far to the north of the Mesabi range. The most numerous bowlders are granite from the Giants range, but southward from the crest of the range these become mingled with the various rocks of the Archean and Huronian formations. Considering the number and character of the bowlders from the rock formations of the Mesabi district, together with the lack of drift along the crest, it is apparent that higher parts of the district have been much cut down by the invasion of the ice.

The till of the Mesabi district makes up in general a confused morainal area, marking one or more pauses in the retreat of the ice toward the north or northeast. Potholes, small lakes, and swamps are characteristic features. From the west end of the district to the neighborhood of Hibbing the till forms a part of what Upham[a] has called the Itasca, or Tenth, moraine (the tenth one back from the most southerly moraine left by the ice). The morainal till from Hibbing to the Embarrass River represents the merging of the Itasca moraine and the Mesabi, or Eleventh, moraine. Eastward from Embarrass River to Birch Lake the till belongs to the Mesabi moraine.

While parts of two great terminal moraines are thus represented in the Mesabi district, these by no means occupy all the district in characteristic form. There are considerable areas in which the drift shows no terminal morainal topography and perhaps would be classified as ground moraine, but in view of its thickness and association in short distances with terminal morainal features the general statement may be made that the till of the Mesabi district, as a whole, is terminal morainal.

[a] Twenty-second Annual Report Geol. Nat. Hist. Survey Minnesota, 1894, pp. 49, 50. See also A. H. Elftman, Am. Geol., Vol. XXI, 1898, pp. 90-109.

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In addition to the till or unstratified drift, there is present a considerable amount of stratified drift—that is, drift modified by water resulting from the melting of the ice—including sand and coarse kame gravels.

Probably associated in origin with the stratified glacial deposits are to be mentioned several peculiar gorges at high elevations which cut directly across the crest of the Giants range. The range is crossed by several marked depressions; the Prairie, Embarrass, and Dunka rivers occupy some of the lower and major ones. But in addition there are a number of small, steep-walled gorges at high elevations which either contain no streams or contain streams very small as compared with the size of the valley. They vary in length, depth, and width. The depressions are at present of U shape, although this may be due to glacial or stream filling in the bottoms. By reference to the general map of the district, a well-marked gorge may be observed in secs. 30 and 31, T. 59 N., R. 18 W., with walls standing 100 feet above the level of the present bottom. A depression across the range may be observed in sec. 7, T. 58 N., R. 16 W. The Duluth and Iron Range Railway follows another in secs. 8 and 17, T. 59 N., R. 14 W. Another may be observed in sections 9 and 16 of the same town and range. Finally, in sec. 17, T. 60 N., R. 12 W., is a small, well-marked gorge with walls standing 40 feet above the present bottom, and exhibiting well-marked terraces (see fig. 5, p. 160) and potholes. The elevation of the bottom of this gorge is over 400 feet above the level of the bottoms of some of the deeper depressions crossing the range. It is apparent that depressions of such widely varying elevations must have been developed under different conditions. Some of the lower and deeper ones, for instance that occupied by the Embarrass Lakes, are doubtless mainly pre-Glacial in origin. The higher ones, it is believed, were due essentially to glacial streams. When the melting of the great ice sheet caused its southern margin to recede to the north of the Giants range there was a ponding of water between the front of the ice sheet and the Giants range, and when the level of the water was high enough it is likely that the water discharged through the lower points in the Giants range. The ridge was already deeply notched by pre-Glacial streams, but as the ice withdrew it left them irregularly filled with glacial material, so that the escaping waters were compelled to make new channels at the lowest points of escape. Even at the present time a thickness of 184 feet of

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drift has been found in the Embarrass Valley. When thus filled the steep-walled gorges at high elevations in the Giants range were carved. At the same time the water was wearing away the drift barriers in the old stream channels. As soon as any considerable volume of water was diverted into these channels the gorges in the rock at the crest of the range were abandoned, for the erosion of the soft drift was much easier than that of the hard rock in which the upper gorges were being carved. The disinterment of the old drainage channels by erosion of the drift has continued to the present time. It is apparent that the abandonment of the rock gorges did not occur simultaneously throughout the range, for some, due to initial depression or to the structure and character of the rock, were cut deeper than others and would be abandoned later. As the water fell in the great glacial lake north of Mesabi the irregularities of the bottom may have caused the water to be divided into several lakes, among them Lakes Norwood and Dunka.[a]

On many of the rock surfaces of the Mesabi district glacial striæ mark the course of the ice across the area. The striæ show minor diversity in direction, but in general they range from S. 10° W. to S. 30° W. At Pokegama Falls and Prairie River Falls there is greater variation, at the former place the direction being S. 50° W. and at the latter a little east of south.

The glacial striæ, together with the character and distribution of the fragments in the drift derived from the cutting down of the Giants range, show that the movement of the ice was essentially from northeast to southwest, as noted by Upham. Todd[b] has maintained that the ice advanced into northeastern Minnesota in two lobes, one through Lake Superior and the other from the north and northeast down the Red River, and on this hypothesis the morainal material on the Mesabi may in part represent interlobate deposits. While the northwestern edge of a Lake Superior lobe may have come nearly or quite up to the Mesabi range, the movement across the range itself was unquestionably from the northeast.

[a] N. H. Winchell, Bull. Geol. Soc. Am., Vol. XII, 1900, p. 125.
[b] Am. Geol., Vol. XVIII, 1896, pp. 225, 226.

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CHAPTER VII.

RÉSUMÉ OF GEOLOGIC DEVELOPMENT AND CORRELATION.

SECTION 1.—RÉSUMÉ OF GEOLOGIC DEVELOPMENT.

During the building of our continent there have been many general elevations and subsidences of vast areas with reference to the sea level, resulting in the alternate pushing back and encroachment of the ocean. The causes of these movements are complex and need not be discussed. That they have actually occurred is shown by the fact that the continent is largely built up of layers of marine deposits, between some of which are marked discordances of structure and profound differences in life remains. The Mesabi district, as shown by the facts given in preceding chapters, has been involved in some of these general movements and has been covered by ocean waters at several times.

The oldest rocks of the Mesabi district, the Archean series, are of igneous origin. For a long period these rocks must have had the district to themselves, for there is evidence that the rocks had been mashed, bent, and broken by slow earth movements, during which mountain masses were, perhaps, formed which had been slowly but deeply cut by surface erosion before the next overlying series was deposited.

The erosion of the area was accompanied and followed by subsidence and by encroachment of the ocean, which deposited the Lower Huronian sediments. The first deposit of the advancing waters was conglomerate, made up of fragments from the Archean rocks. As the waters grew deeper over the Mesabi district, or the conditions changed in other ways, finer detrital débris was deposited, which, when hardened and metamorphosed, became graywacke and slate.

After a time sufficient to allow the deposition of fine-grained Lower Huronian sediments to a thickness of 5,000 feet or more, there was an

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elevation and folding of the area and a consequent falling back of the ocean waters. This was either accompanied or followed by the intrusion of granite and the metamorphism of the Lower Huronian strata. As a result of the elevation, the folding, and the intrusion of granite, mountain masses were produced, which were slowly worn down by erosion. This sequence of events is evidenced by the truncated folds in the Lower Huronian strata. A vast period of time must have been required to accomplish these results.

The degradation and subsidence of the area and the encroachment of the ocean brought on conditions for the deposition of the Upper Huronian series. The first deposit of the Upper Huronian sea, as usual, was one characteristic of shallow waters, conglomerate and sand (Pokegama formation). When the conditions changed iron formation and mud (Biwabik and Virginia formations) were deposited. Between the deposition of the Pokegama formation and the deposition of the Biwabik and Virginia formations there was probably another slight oscillation of the land, which perhaps even brought the Pokegama formation above water, for we find at the base of the iron formation a thin layer of conglomerate, indicating a brief period of shallow waters and wave action just preceding the deposition of the iron formation. The Biwabik iron formation was in the main deposited before the Virginia formation, but the change from one to the other did not occur evenly through the range. While the iron formation was still being deposited in the western part of the area, mud was being deposited in the eastern part, and furthermore, unusual currents or minor oscillations were carrying mud layers into the area in which the main deposit was of iron-formation material. This sequence of events is shown by the gradation of the iron formation into slate when following the range east from the central part of the district, and by the interstratification of slate layers with the iron formation in other parts of the district.

The Upper Huronian sea may not have covered the area immediately north of the Giants range; in other words, the Giants range may have formed the northernmost shore line of at least a part of this ocean, for notwithstanding repeated search on the north side of the Mesabi range and in the area between this range and the Vermilion range, and even in the Vermilion range itself westward from its connection with the Mesabi range, no trace of Upper Huronian sediments has been found, and while erosion could have

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accomplished this result, the fact that the series is so well developed to the south side of the Giants range, and its continuation is entirely lacking north of the Giants range, suggests the possibility of a shore line. The fact that the area north of the Giants range is underlain by Archean and Lower Huronian rocks would seem to indicate that the general area north of the Giants range, including the major portion of the Vermilion district, may have been an anticline and above water during Upper Huronian deposition. On the other hand, the Upper Huronian rocks are known to have very widespread distribution in the Lake Superior country, and it is quite possible that they may have entirely covered the supposed anticline northward from the Giants range and have since been removed from this area by erosion, which would naturally cut down the anticlinal area first.

If there was a shore line along the Giants range during the deposition of the Upper Huronian sediments, the sediments would have had a slight initial dip to the south, due to original deposition in this position against the shore. It is probable, however, that the general southerly tilting now shown by the Upper Huronian strata is due mainly to subsequent folding.

The deposition of the Upper Huronian series was followed by an elevation and slight folding and a pushing back of the ocean waters, and this in turn by a long period of induration and erosion. For most of the district erosion did not cut through the Virginia slate before the advent of the Keweenawan, but at the east end of the district the slates were probably removed and the iron formation exposed.

In Keweenawan time the Duluth gabbro mass of northeastern Minnesota was intruded between the Upper Huronian series and any sediments which may have overlain it and greatly metamorphosed the rocks with which it came in contact. There is no direct evidence of Keweenawan sediments and surface flows having overlain the Mesabi district, but if they were ever present, as they may have been, judging from the facts observed in other parts of the Lake Superior region, the district must have undergone another submergence in Keweenawan time prior to the intrusion of the gabbro.

The gabbro is now found to lap diagonally over the Virginia slate and the iron formation and to rest on the eroded edges of both, showing that the post-Huronian erosion had cut through the slate for a part of the district, as above noted. If such erosion had not occurred, it would be necessary to suppose the gabbro to have been intruded along an even

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plane gently inclined to the stratification of the Upper Huronian series. Moreover, the relation of this erosion plane to the Upper Huronian strata is such as to indicate that the tilt of the strata was either to the south or to the west prior to the erosion which pared down the surface.

The gabbro intrusion was followed by an intrusion of granite in the eastern end of the district, which greatly metamorphosed the Upper Huronian strata with which it came into contact. The time of the intrusion is post-Huronian, and in view of the fact that granites have been found cutting the Keweenawan (and not the Cambrian) in other areas, it is thought that the intrusion in the Mesabi district occurred in Keweenawan time.

At some time after the Keweenawan, and before the deposition of the Cambrian, the Upper Huronian and Keweenawan rocks (and of course all underlying rocks) were folded. This folding was mainly responsible for the gentle southward tilting of the Upper Huronian strata of the Mesabi district. It was also responsible for the final elevation of the area, the erosion remnant of which is now known as the Giants range. Evidence that the main folding of the Upper Huronian occurred in post-Keweenawan, rather than pre-Keweenawan time, is lacking in the Mesabi district itself; in fact, the only positive evidence there to be observed is that the Upper Huronian series was slightly folded and truncated before Keeweenawan time, as shown by the relation of the formation to the Keweenawan. But in other parts of the Lake Superior country the two series have been uniformly folded together and owe their present attitudes essentially to this folding, and it is not probable that the limited area of the Mesabi alone escaped this movement.

During Paleozoic and most of Mesozoic time, represented in other districts by deep accumulations of sediment, the Mesabi district was probably above water and undergoing erosion, for we find no traces of such deposits in this or adjacent districts. Yet it is not certain that the Cambrian may not have covered the area, for it is known to have a widespread distribution in the Lake Superior country and to have been stripped of great areas by erosion. It is now found in areas almost as high as the Giants range, as, for instance, the Menominee district of Michigan. Toward the close of Mesozoic time, in the Cretaceous period, there came a subsidence of the area with reference to the ocean level, and the Cretaceous ocean encroached over the part of the area westward from Virginia and probably extended eastward from Virginia, but how far no evidence is as yet at hand to show.

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With the subsequent emergence of the Mesabi district from the Cretaceous ocean, the district appeared in approximately its present condition so far as rock succession and structure are concerned.

After another long period, represented in other parts of the United States by deposition of Tertiary sediments, during which erosion greatly modified the surface of the land, the great North American continental ice sheet of Pleistocene age pushed its southern margin over the Mesabi district. The granite of the Giants range bore the brunt of the attack from the north and consequently was much cut down by the ice, but all the other formations of the district, including the iron formation, were truncated to a considerable depth. This is shown by the abundant drift in the district largely composed of local material. The drift for the most part conceals the older rocks along the southern slopes. When the melting of the ice sheet had caused the margin to recede north of the Giants range, it is probable that a considerable body of water was ponded between the ice front and the crest of the Giants range, and when high enough the water escaped through the lower places in the range, and in so doing gouged out some of the remarkable small steep-walled gorges now to be observed at a number of points in the granite at the crest of the range.

Since Glacial time ordinary erosion agencies have been at work. Where, as in the upper and eastern portions of the range, glacial drift is thin or lacking, drainage channels have followed the old ones formed before the Glacial epoch. On the lower slopes of the range, and particularly in the western portion, the drainage has been feebly struggling to perfect itself in the great irregular mass of glacial débris, but thus far with little success.

Since the emergence of the Upper Huronian series from the sea and the removal of the Virginia slate, the rocks of the Biwabik iron-bearing formation have been continuously undergoing alterations, part of which have resulted in the concentration of the iron-ore deposits of the district. The nature and progress of this alteration are discussed in Chapter VIII.

Such, in brief, is the history of the district as shown by the succession, structure, and relations of the rock strata. It is apparent that the development of the Giants range has been a complex process. Its first recognizable elevation occurred at the time of the Lower Huronian folding and intrusion of granite. At the time of the inter-Huronian erosion the elevation was greatly reduced, and the Upper Huronian sea may have entirely submerged it. Yet it is possible that it may have remained sufficiently high to form

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the shore line of a portion, at least, of the Upper Huronian sea. Some of the spurs of Archean and Lower Huronian rocks also, as, for instance, the one running out toward Eveleth, may have existed either above or below water during the time the Upper Huronian sea was depositing sediments in the area. After the deposition of the Upper Huronian the range was again elevated and gently folded. Before the Keweenawan it was considerably reduced by erosion, for in the east end of the district the Keweenawan gabbro rests upon the truncated edges of the Upper Huronian rocks. After Keweenawan time the range was further folded and uplifted. Indeed, its major elevation was probably developed at this time. From Keweenawan to Pleistocene time erosion cut down the range, except during the Cambrian and Cretaceous periods, when the process was perhaps replaced by deposition. In the Glacial epoch the range was further cut down by glacial erosion. And, finally, since Pleistocene time, subaerial erosion has perhaps very slightly reduced the portions of the range not covered by glacial drift.

SECTION II. CORRELATION.

In the Lake Superior region R. D. Irving, followed by C. R. Van Hise, and their assistants on the United States Geological Survey, have discriminated four great pre-Cambrian series:

(1) The Basement Complex or Archean, consisting mainly of igneous rocks, but containing also sedimentary rocks in small quantity.

(2) The Lower Huronian, a sedimentary series resting unconformably upon the Archean.

(3) The Upper Huronian, another sedimentary series resting with well-marked unconformity upon both the Archean and Lower Huronian.

(4) The Keweenawan, a series of intercalated lavas and sediments resting unconformably upon all the underlying rocks.

The Huronian and Keweenawan series together make up the Algonkian system. For a full discussion of these great series, the development of knowledge concerning them, their relations, their subdivisions, and their local names, the reader is referred to the reports of the United States Geological Survey.[a]

The series above named had been studied in detail and their relations

[a] See particularly Bull. 86, and Sixteenth Ann. Rept., Pt. I, pp. 780-807; see also correlation chapters in Monographs XIX, XXVIII, XXXVI, and XLV.

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determined in the other iron-bearing districts of the Lake Superior region before the Mesabi district had been systematically studied by the Survey.

In the Mesabi district the gabbro has been assigned by all to the Keweenawan. The upper, flat-lying series of the Mesabi district has been generally recognized as the equivalent of the Animikie series of the international boundary, eastward from Akeley and Gunflint lakes to Thunder Bay, and has indeed been called Animikie by nearly all who have had occasion to refer to the series. (See Chapter II.) Irving and Van Hise have correlated the Animikie series with the original Upper Huronian series as worked out on the north shore of Lake Huron. This correlation has been consistently followed by the United States Geological Survey in its work on the Lake Superior region, although the correctness of the correlation is disputed by a number of the Canadian and Minnesota geologists, who maintain that the Animikie series is later than the true Upper Huronian. The controversy as to the equivalence of the Animikie and the Upper Huronian will not be gone into, but the correlation by the United States Geological Survey will be accepted as a basis for the correlation and naming of the Animikie and underlying series in the Mesabi district. Professor Van Hise has now in preparation a final monograph on Lake Superior geology in which the question of the correlation of the Animikie will be fully discussed in the light of recent field work in the Lake Superior region.

The rocks underlying the "Animikie" or Upper Huronian of the Mesabi district were lumped together as Keewatin and described as essentially igneous by the geologists of the Minnesota survey, and largely because of this were formerly correlated with the Basement Complex or Archean by the United States Geological Survey. When systematic work was done in the Mesabi district by the United States Geological Survey it was found that the supposed Archean Complex or Keewatin series, underlying the Upper Huronian, really consists of two series, one igneous and the other sedimentary, which correspond respectively in their relations and lithological character with the Archean and Lower Huronian series of other parts of the Lake Superior region, particularly the Vermilion district of Minnesota.

Thus, each of the four great divisions of the pre-Cambrian previously worked out by the United States Geological Survey for the Lake Superior

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region as a whole was found to be represented in the Mesabi district. Perhaps in no other district is the proof of their existence and relations any more decisive than here, and the Mesabi may well serve in these features as the type pre-Cambrian district of the Lake Superior region.

If the Minnesota survey had divided the Keewatin of the Mesabi district into the Upper and Lower Keewatin, as suggested by Grant, and had included the separately mapped greenstones and mica-schists in the Lower Keewatin, it may have been that the succession of the Minnesota survey would have been identical geologically with that of the United States Geological Survey. It may be asked, then, why the terms "Upper Keewatin," "Lower Keewatin," and "Taconic" or "Animikie" should not have been retained for the Mesabi formations. A perusal of the summaries of literature in Chapter II will show that these terms have been used from time to time and from place to place in a great variety of senses. As at present used in northern Minnesota, Upper Keewatin and Lower Keewatin each include rocks which the United States Geological Survey has designated as Archean and Lower Huronian. Moreover, the terms "Huronian" and "Archean" had been applied to similar series in other parts of the Lake Superior country before the term "Keewatin" was introduced, and should therefore have been retained for Minnesota. The term "Taconic" has been used as an equivalent to Lower Cambrian, and includes both Keweenawan and Animikie rocks. The work of the United States Geological Survey has demonstrated the presence of a great unconformity between the Cambrian and the Keweenawan, and between the Keweenawan and the Animikie, and hence the term "Taconic" could not be retained for these two unconformable series, even if the term "Animikie" had not priority in the Lake Superior region and the term "Taconic" wholly discredited in the eastern United States, where the term was first applied.

The remarkable similarity of the Upper Huronian of the Mesabi district to that of the Penokee-Gogebic district has been often remarked. The succession within the series is the same. The relations to adjacent series are similar. Scarcely a phase of rock in one series can not be matched in the other, although in varying abundance. The Upper Huronian of the Mesabi district is on the north shore of Lake Superior and dips to the south at a low angle. The Upper Huronian of the Penokee-Gogebic district is on the south side of Lake Superior and dips to the north at a

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high angle. These facts, taken together with the synclinal structure of the Lake Superior Basin, indicate that the Upper Huronian series of the Mesabi and the Penokee-Gogebic districts form, respectively, the north and south limbs of a great basin into which the Upper Huronian series has been folded and within the limits of which also the series was probably originally deposited.

The hypothetical course of the truncated edges of the Upper Huronian strata connecting the two districts is indicated by the broken line in fig. 8. The area south of the Mesabi range is low and swampy for a considerable

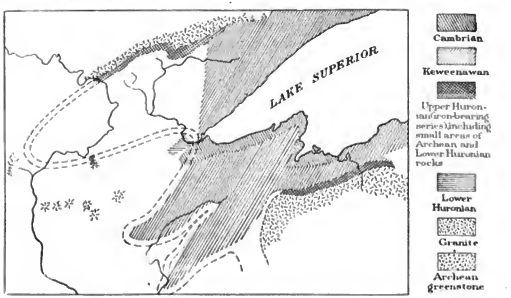

FIG. 8.—Sketch showing possible connection of the Mesabi with Penokee-Gogebic iron-bearing series.

distance, and this area is presumably underlain by the Upper Huronian slate, which is soft, easily eroded, and has a synclinal structure. In the vicinity of Carlton and Cloquet, on the St. Louis River, are graywackes and slates standing on edge, which resemble the Lower Huronian series of the Mesabi district and are presumably themselves of Lower Huronian age. About 12 miles east of Aitken, Minn., south of the town of Kimberly, are two exposures of quartzite identical in character with the Pokegama quartzite of the Mesabi range. To the south of this quartzite is greenstone identical with the Archean greenstone of the Mesabi district. To the west and south outcrops of granite and greenstone, presumably of Lower Huronian

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and Archean age, are known at a number of localities, as shown on the map. The Upper Huronian series for this part of the region may lie within the limits of the area thus outlined by the Lower Huronian and Archean rocks, and the outcrop of quartzite, which is presumably Upper Huronian, would indicate that the southern arm of the Upper Huronian syncline actually comes up close to the edge of the area so outlined. To the north of the quartzite exposure at Kimberly referred to is iron-formation débris in the drift and a faint line of magnetic attraction extending in a direction nearly east and west from the quartzite. Moreover a faint line of magnetic attraction has been carried some distance west of Grand Rapids. It must be assumed that the Upper Huronian belt passes north of Carlton and Cloquet. Its course in the area between these places and the Penokee-Gogebic district is not shown by any direct evidence, but it seems probable that it must connect with the Penokee-Gogebic district by a complex fold for this reason: The occurrence of the Keweenawan and Upper Huronian rocks in the Penokee-Gogebic district and other parts of the Lake Superior region indicates that the two series received their major folding together, and the folds or tongues in the Keweenawan rocks shown on the map are likely to have their counterparts in the Upper Huronian strata below. The truncated edges of the Upper Huronian strata may therefore appear in somewhat the position shown on the map. But where the distribution of the series can be worked out the series is known to pass under the Keweenawan for considerable distances, as in parts of the Mesabi and Penokee-Gogebic districts, and it is more than likely that through the unknown connecting area the iron formation is actually covered by the Keweenawan over considerable areas. Also, during the erosion period between Upper Huronian and Keweenawan time, the entire Upper Huronian series, including the iron-bearing formation, may have been wholly removed for long distances, and thus the Keweenawan lies against the Lower Huronian or the Archean without intervening series equivalent to the Mesabi. But so far as the Upper Huronian still occurs at the surface it is likely to be found close to the edge of the Keweenawan, and for this reason the dotted line is drawn nearly parallel to the periphery of the Keweenawan.

That the Upper Huronian strata of the Mesabi and Penokee-Gogebic districts were originally connected no one will doubt who examines them

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and realizes their identity in character. That the eroded edges of the Upper Huronian folds have the position indicated on the map is largely hypothetical, but is in accord with the known facts and inferences derived from them. Explorations in search for the iron-bearing member of the Upper Huronian series beyond the known distribution in the Mesabi and Penokee-Gogebic districts ought first to be made on some such assumption as to distribution and carried into other areas as the developed facts warrant.

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CHAPTER VIII.

THE IRON-ORE DEPOSITS.

DISTRIBUTION.

On the accompanying geologic map of the Mesabi district the principal properties underlain by iron ore of present commercial value are indicated by shading and names. The ore deposits do not occupy all the area shaded, but each of the shaded areas contains some iron ore. The following features of distribution of the iron ore may be especially noted: The deposits are numerous through the central portion of the district, and they are altogether lacking in the extreme eastern and western portions. In the central portion of the district they have a tendency to occur in groups, with the intervening areas showing few or no deposits. The largest group of mines in the district, and for that matter probably the largest group of iron-ore deposits of such quality and size in any known equivalent area in the world, is in the vicinity of Hibbing. In the district as a whole, the deposits are less numerous and less in bulk adjacent to the north and south boundary of the iron-bearing formation than in the middle horizon, though there are numerous and marked exceptions to this statement. It is safe to say that a line drawn parallel to the trend of the district, halfway between the north and south boundaries, would cross the large majority of the deposits. Assuming the ore to occupy about one-fourth of the areas shaded, the proportion of the area of the ore deposits to the total area of the iron-bearing formation of the district is, roughly, 5 per cent, and for the area between the Hawkins mine and Mesaba station the iron ore occupies 8 per cent of the area of the iron formation.

While no iron ore has been found in the few holes that have penetrated the solid Virginia slate and entered the underlying formation, it is not satisfactorily proved by actual drilling that iron-ore deposits do not occur in this part of the iron-bearing formation. Iron ores have been found in

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and associated with slate layers in the iron-bearing formation and also just under the edge of solid black Virginia slate. Yet certain facts discussed in connection with the origin of the ores indicate but small probability of finding ores any considerable distance under the Virginia slate.

The western portion of the range, west of Hawkins mine, shows few deposits and these are of comparatively low grade. No adequate reason is known why high-grade ores should not be found there in quantity, but the considerable amount of drilling thus far done in this area has not disclosed them. Certainly the holes put down in this part of the range have disclosed far less high-grade ore than any equivalent number of holes as widely distributed through the central portion of the range.

The iron formation in the eastern part of the Mesabi district, east of Mesaba station, is well exposed and has been much explored. Indeed, considerable exploration was done here before the central portion of the range was discovered. Yet no merchantable deposits of ore have thus far been discovered. It is thought that little or no high-grade ore is likely to be found here for reasons given on pages 272–274.

SHAPE.

The shape of the ore deposits can not be better described than by saying that the rock bottoms on which they lie form shallow, irregular basins, usually with greater horizontal than vertical dimensions, although rarely the reverse. These basins have all the complexity and relations to other troughs of ordinary surface-drainage basins in driftless areas. Indeed, topographic maps of the bottoms of most of the Mesabi iron-ore deposits would serve fairly well as maps of typical surface-drainage basins. The basins may be fairly simple with only minor irregularities; they may slope gently on one side and steeply on the other; there may be overhanging shelves on one or both banks; there may be salients and recentrants; there may be islands of rock; there may be irregularities in their bottoms resulting in their longitudinal or transverse division; there may be tributary channels coming in from the sides. The bottoms of the basins seldom show gentle slopes, but are terraced, the slopes of the terraces corresponding to the dip of the iron-formation strata. Usually the rock basins containing the ore have a very considerable pitch; the difference in elevation of the two ends may be as much as 100 feet. The lower portions

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of the basins containing ore are commonly below the level of the outlets. The upper sides of the ore deposits are usually irregular and perhaps slightly below the level of the surrounding rock surfaces. These features are due to differential erosion and to the scraping of the glaciers which have passed over them. Because of this fact and because also of the irregular covering of glacial drift the pits of the rock basin in which the ore deposit lies may not be apparent at the surface. Finally, the longer directions of the ore basins may be either parallel or transverse to the trend of the range.

A topographic map of the bottom of a typical, somewhat irregular Mesabi iron-ore deposit, the Adams, is represented in Pl. XXIII.

SIZE.

The Mesabi iron-ore deposits have horizontal dimensions varying from a few feet to almost 2 miles. Commonly, they show considerable extension in one direction. The widths seldom exceed a quarter of a mile, while the lengths are not uncommonly a half mile or more.

The thickness rarely reaches 350 feet and is commonly less than 200 feet. Many deposits not over 60 feet in thickness are being mined. The maximum depths of the workings of some of the mines are given in the following table:

Maximum depth of mines in Mesabi district.

[June, 1902.]

	Feet.
Adams	205
Burt	120
Duluth	97
Biwabik	110
Mahoning	75
Sparta	125
Malta	110
Pillsbury	73
Spruce	211
Stevenson	40
Hull	176
Rust	192
Sellers	138
Auburn	218
Geneva	174
Fayal	168
Mountain Iron	150

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KINDS OF ORE.

The Mesabi iron ores are for the most part slightly hydrated hematites with an average of 3 per cent of combined water shown by cargo analyses. It is likely that the true percentage of combined water may be somewhat larger than this, for before it is measured the ore is dried at 212° F., a temperature sufficient to drive off some of the combined water. Associated with the slightly hydrated ores are abundant layers of ores of varying thickness differing from hematites only in their higher percentage of combined water. They include turgite, 2 Fe_2O_3 (94.7 per cent), H_2O (5.3 per cent); goethite, Fe_2O_3 (89.9 per cent), H_2O (10.1 per cent); limonite, 2 Fe_2O_3 (85.5 per cent), 3 H_2O (14.5 per cent); and possibly even xanthosiderite Fe_2O_3 (81.6 per cent), 2 H_2O (18.4 per cent). Magnetite is present, but very sparsely, in the ore deposits.

The slightly hydrated hematites are usually dull blue-black or brown earthy varieties. The hard blue crystalline hematites are rare and the brilliant specular hematites altogether lacking. The more hydrous ores are for the most part soft, earthy varieties. Most of them are locally called yellow ocher, or brown ore, but they include also hard crystalline varieties. Rarely both the hematite and hydrous ores appear in stalactitic or botryoidal forms which are likely to be observed bordering cavities in the ore. Under the microscope the hematites appear only as dull-red and black opaque aggregates, and the hydrous ores as dull-yellow opaque aggregates, but when examined in hand specimens they are seen frequently to be made up of small ellipsoidal granules identical in size and shape to the greenalite granules of the greenalite rocks described on pages 101–115. The magnetite, when present, is black and crystalline, occurring typically in octahedra.

East of the Iron Range track, through most of range 14, and all of ranges 13 and 12, the oxide is largely magnetite, which has not been segregated into deposits of sufficient extent to warrant exploitation. Westward from Mesabi station the magnetite gives way rapidly to more or less hydrous hematite, and through the central and western portions of the range is found in but small quantity.

Slightly hydrous hematites and the more hydrous ores are almost everywhere interbanded in thin or thick layers, yet in most deposits con-

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siderable zones are composed predominantly of one or the other class of ores. The hydrous ores are more abundant near the tops of the deposits, as in the Mahoning, Sharon, Clark, Oliver, Genoa, Sparta, Elba, Commodore, Biwabik, Duluth, and Hale mines. To less extent they appear in middle and lower horizons in the deposits.

MINERALS AND ROCKS CONTAINED IN THE ORE.

The principal mineral constituent associated with the ore is chert or quartz. Average cargo analyses of the ores show about 4 per cent of silica, but locally the percentage of silica in the ores runs much higher. There may be found all stages in the gradation, from ore with a low percentage of chert to ferruginous chert with only a low percentage of iron. Ferruginous chert forms the wall rocks of the deposit, occurs as pillars, horses, or shelves projecting from the bottoms or sides, and occurs as small or large masses entirely included in the ore. Even where the percentage of chert is as low as 4 per cent the substance may be observed in minute grains with the microscope.

Rarely a layer of the ferruginous chert in a deposit may be so disintegrated that it is a soft, light-yellow powder resembling fine sand or tripoli powder. The particles are entirely angular. Analyses published by Spurr give the following results:

Analyses of silica powder.[a]

Constituent.	Per cent.	Per cent.
SiO_2	77.89	98.17
Al_2O_3	13.55	.50
Fe_2O_3	1.83	1.03
MgO	.36	Trace.
CaO	Trace.	Trace.
Na_2O	.58	.25
K_2O	.84	Trace.
H_2O-	4.45	
H_2O+		
Loss on ignition		.19
	99.50	100.14

[a] Geol. Nat. Hist. Survey Minnesota, Bull. No. 10, pp. 81 and 214.

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Other similar layers, somewhat coarser, are found on examination to consist of waterworn sand (to be discriminated from the "sandy" ores described in the subsequent paragraph). Some of the sand layers are certainly the result of washing in of glacial sand along cracks from above, as the layers have been connected with the surface and consist of fragments of all the minerals found in the drift, but others may represent a disintegration of original sandy layers in the iron formation.

In the western end of the range some of the iron ores contain so much disseminated "sand" that up to 1902 they were considered unfit for use. The "sand" is uniformly disseminated through the ore, or occurs as more or less iron-stained layers. Under the microscope the "sand" is seen to consist not of water-rolled particles, but of subangular fragments of chert derived from the disintegration of the ferruginous chert. All stages of the disintegration may be observed from a typical ferruginous chert, in which the former existence of greenalite granules is indicated by the distribution of chert and iron oxide, to the loose particles of chert which to the naked eye look like sand. In the less disintegrated phases the polygonal and angular particles of chert may be seen to be separated by thin films of iron oxide, showing the cementation of the particles to be very weak. The disintegrated chert may be separated from the ore by washing, but whether or not this can be done successfully on a commercial basis is a question not yet satisfactorily decided. Experiments thus far conducted, while not decisive, indicate that it can be done.

A small quantity of grünerite and actinolite in columnar forms or in radial sheaves may occasionally be seen associated with the chert and ore, especially in the ore containing considerable magnetite.

Crystals of calcite, siderite, dolomite, quartz, adularia, pyrite, mica, pyrolusite, and many other minerals are common in vuggs.

It is not known in what mineral form the phosphorus occurs in the ores, although it will be shown on a subsequent page that it occurs probably in combination with alumina.

In the Michigan ranges Prof. A. E. Seaman, of the Michigan School of Mines, has determined the phosphorus to occur largely in the form of apatite. Apatite has been searched for in the Mesabi ores, but has not been found in clearly identifiable crystals. Other phosphorus minerals,

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such as vivianite, wavellite, wagnerite, and collophanite, have been looked for, but without success.

Layers of paint rock, ranging in thickness from a fraction of an inch to several feet, occur in almost every deposit. Kaolin, or clay layers, either white or yellow, and not sufficiently discolored by iron to warrant the name "paint rock," are also occasionally to be seen.

Ferruginous slate, differing from the normal ores only in containing a higher percentage of alumina, forms layers in the ore deposits.

Occasionally a small mass of bluish-black ore is encountered which runs high in manganese in the form of pyrolusite.

Vein quartz, usually much brecciated, is a common feature in the ore deposits. It usually follows irregular joints and fault zones, and occasionally follows the bedding for a considerable distance. The brecciation is direct evidence of considerable movement in the deposit subsequent to the introduction of quartz.

Iron pyrites is rarely to be observed in quantity; it is known to be sufficiently abundant to lower the value of the ore only along the edge of two deposits on the range.

Still other rare rocks or minerals in the ore deposits could be mentioned. In the Fayal mine is a peculiar bluish rock with a greasy feeling, showing slickensides. It is a rock rich in magnesium and colored by ferrous iron. Its origin is not known, nor is it important.

CHEMISTRY.

The following statements concerning the composition of the Mesabi ores are based on official cargo analyses, as published by the American Iron and Steel Association, on a great number of detailed figures furnished by mining superintendents, engineers, and chemists on the Mesabi range, and finally on general statements made by those best qualified to make them. Among those who have given especially full information on this subject should be mentioned the Lerch brothers, chemists, of Hibbing, Virginia, and Biwabik; Mr. R. B. Green, chemist of the Minnesota Iron Company; Mr. E. T. Griese, chemist of the Duluth, Missabe and Northern docks at Duluth; Mr. A. P. Silliman, mining engineer and chemist, Hibbing; Mr. A. T. Gordon, chemist, Mountain Iron; Mr. E. J. Johnson, chemist of the Republic group. To mention superintendents and mining engineers who have given infor-

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mation would be to give a list of those connected with Mesabi mining. It must not be understood that each of the above-named gentlemen would agree with all of the following statements. Indeed, there is much minor diversity of opinion.

Average cargo analyses of Mesabi ores shipped in 1901, according to figures compiled by the Iron and Steel Association, are as follows:

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Analyses of ores of Mesabi range.

[The upper line of figures opposite each ore represents its analysis when dried at 212° F.; the lower line when in its natural condition.]

Ore.	Iron.	Phosphorus.	Silica.	Manganese.	Alumina.	Lime.	Magnesia.	Sulphur.	Loss by ignition.	Moisture.
Adams (Adams mine)	62.75	0.034	3.49	0.706	1.08	0.148	0.080	0.065	4.57	.....
	56.719	.0307	3.154	.6381	.976	.1337	.0723	.0587	4.130	9.61
Adams Special (Adams mine)	63.61	.032	3.09	.574	1.30	.119	.079	.047	3.87	.....
	57.497	.0289	2.793	.5188	1.175	.1075	.0714	.0424	3.498	9.61
Adams No. 2 (Adams mine)	59.93	.009	4.01	.662	2.29	.130	.088	.073	6.79	.....
	50.940	.0586	3.476	.5627	1.946	.1105	.0748	.0620	5.771	15.00
Admiral (Commodore mine)	63.800	.027	4.900	.300	.620	.230	.180	.006	2.140	.....
	58.823	.024	4.517	.276	.571	.212	.165	.005	1.973	7.800
Atlas (Malta mine)	60.53	.057	5.70	1.07	1.03	.20	.10	.013	4.73	.....
	54.2228	.0511	5.1061	.9585	.9227	.1792	.0896	.0116	4.2371	10.42
Audrey (Auburn mine)	61.66	.054	4.20	.54	2.30	.38	.20	.002	4.16	.....
	53.311	.0466	3.631	.466	1.988	.328	.172	.0017	3.596	13.54
Beaver (Mahoning mine)	63.85	.078	2.35	.33	1.54	.18	.12	.011	3.95	.....
	57.24	.0699	2.106	.29	1.38	.16	.107	.0098	3.54	10.35
Biwabik (Biwabik mine)	63.56	.038	3.10	.45	.95	.19	.11	.009	4.13	.....
	58.64	.035	2.86	.415	.876	.175	.10	.008	3.81	7.72
Butler (Biwabik mine)	62.59	.053	2.52	.50	1.02	.41	.28	.015	5.08	.....
	56.88	.048	2.29	.454	.926	.372	.254	.013	4.61	9.12
Chisholm (Chisholm mine)	64.30	.039	3.36	1.15	1.02	.18	.20	.006	.....	.....
	57.471	.0348	3.003	1.027	.911	.160	.178	.0053	.....	10.62
Clark (Clark mine)	62.82	.034	1.68	1.04	.96	.23	.18	.005	.....	.....
	56.148	.0303	4.182	.929	.858	.205	.160	.0044	.....	10.62
Commodore (Commodore mine)	63.100	.039	4.150	.200	1.210	.240	.060	.004	3.400	.....
	57.231	.035	3.764	.181	1.097	.217	.054	.003	3.083	9.300
Columbia (Columbia mine)	57.52	.066	8.89	.56	3.94	.13	.13	.016	4.58	.....
	49.28	.056	7.62	.48	3.37	.11	.11	.014	3.92	14.33

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Analyses of ores of Mesabi range—Continued.

Ore.	Iron.	Phosphorus.	Silica.	Manganese.	Alumina.	Lime.	Magnesia.	Sulphur.	Loss by ignition.	Moisture.
Corsica (Corsican mine)	61.00	0.045								
	54.21	.0400								11.10
Croxton (13-58-20, Croxton mine)	60.00	.060								
	54.60	.0546								9.00
Bailey (Spruce mine)	61.03	.038	6.11	0.71	0.952	0.21	0.18	0.043	5.17	
	54.54	.032	5.157	.599	.776	.177	.15	.038	4.96	15.50
Duluth (Duluth mine)	59.93	.053	5.23	.883	1.02	.118	.169	.010	6.53	
	52.492	.0464	4.580	.7734	1.418	.1033	.0654	.0087	5.544	12.41
Ella (Ella mine)	61.70	.059	3.84	.93	.89	.10	.17	.010	5.20	
	55.7891	.05329	3.4721	.8409	.8047	.0904	.1537	.0090	1.7018	9.56
Fayal (Fayal mine)	62.80	.037	2.95	.45	.75	.40	.15	.044	2.69	
	57.8803	.0335	2.675	.589	.680	.362	.136	.0396	3.346	9.31
Franklin (Franklin mine)	60.035	.0301								
	55.508	.0252								7.467
Genoa (Genoa mine)	62.88	.032	4.62	.46	.77	.44	.22	.007	3.44	
	56.453	.0287	4.147	.412	.691	.395	.197	.0062	3.088	10.22
Hartley (Lake Superior mines)	63.45	.042	3.65	.502	1.24	.150	.078	.008	3.50	
	57.806	.0381	3.313	.5041	1.125	.1361	.0254	.0072	3.177	9.21
Hibbing (Hull mine)	64.02	.033	2.84	.507	1.32	.135	.083	.007	2.50	
	57.899	.0296	2.544	.4542	1.192	.1208	.0745	.0062	2.253	10.40
Island (Fayal mine)	61.40	.066	3.43	.56	.91	.49	.225	.015	5.96	
	54.179	.0582	3.026	.494	.802	.432	.202	.0114	5.259	11.76
Jordan (Jordan mine)	63.040	.050	4.200	.260	1.050	.280	.180	.006	2.760	
	57.685	.053	3.809	.235	.952	.253	.163	.005	2.503	9.300
Juniata (Mountain Iron and oliver mines)	61.45	.054	5.35	.280	2.43	.115	.075	.011	3.45	
	53.205	.0468	4.640	.2428	2.107	.0992	.0650	.0095	3.166	13.354
Kanawha and Hale (Kanawha and Hale mines)	59.10	.060	8.78	.45	1.19	.95	.14	.010	2.69	
	52.0718	.0519	7.7884	.4041	1.0088	.8531	.1257	.0088	1.8788	10.20

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Analyses of ores of Mesabi range—Continued.

Ore.	Iron.	Phosphorus.	Silica.	Manganese.	Alumina.	Lime.	Magnesia.	Sulphur.	Loss by ignition.	Moisture.
Longyear Bessemer (5 and 6-57-20, Longyear mine)	61.00	0.050								
	55.51	.0455								9.00
Longyear non-Bessemer (Longyear mine)	60.00	.070	6.50	0.49	1.21	0.25	0.17	0.010		
	54.60	.0637	5.915	.4459	1.0631	.2275	.1547	.0091		9.00
Mahoning (Mahoning mine)	64.66	.047	2.45	.39	1.46	.14	.12	.008	2.97	
	57.93	.042	2.19	.349	1.308	.12	.107	.007	2.66	10.40
Malta (Malta mine)	63.52	.030	4.70	.78	.63	.12	.12	.013	2.80	
	58.1526	.02747	4.3029	.7141	.5768	.1099	.1099	.0119	2.5634	8.45
Minerva (Minerva mine, formerly Fay)	61.73	.032								
Morrow (Morrow mine)	60.00	.060	5.50	.47	1.32	.12	.08	.027		
	54.90	.0549	5.0325	.43	1.2078	.1098	.0732	.0247		8.50
Mountain (Mountain Iron and Oliver mines)	63.78	.0415	3.95	.219	1.95	.106	.070	.014	2.35	
	55.833	.03632	3.457	.1917	1.707	.0927	.0612	.0122	2.057	12.459
Oliver (Oliver mine)	62.64	.0498	4.63	.232	2.18	.096	.087	.015	3.04	
	54.702	.04348	4.043	.2026	1.903	.0838	.0759	.0130	2.654	12.671
Pearce (Pearce mine)	63.00	.035	3.17	1.10	1.01	.18	.20	.007		
	56.70	.0315	2.853	.990	.909	.162	.180	.0063		10.00
Penobscot (Penobscot mine)	59.82	.040	7.22	.88	1.93	.20	.14	.10	3.53	
	53.18	.035	6.419	.78	1.71	.177	.12	.088	3.138	11.09
Pillsbury No. 1 (Pillsbury mine)	62.07	.030	4.28	.507	1.23	.090	.171	.008	4.84	
	56.707	.0274	3.910	.4631	1.123	.0822	.1562	.0073	4.421	8.64
Pillsbury No. 2 (Pillsbury mine)	59.04	.055	4.92	.750	1.28	.118	.215	.010	8.23	
	52.191	.0486	4.349	.6630	1.131	.1043	.1900	.0088	7.275	11.60
Preble (Mountain Iron and Oliver mines)	60.67	.063	6.22	.325	2.63	.116	.065	.013	3.63	
	52.412	.0544	5.373	.2807	2.272	.1002	.0561	.0112	3.135	13.611
Roberts (Roberts mine)	60.95	.025	7.90	.45	1.13	.25	.08	.040	2.10	
	55.525	.0227	7.196	.4099	1.0294	.2277	.0728	.0364	1.9131	8.90

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Analyses of ores of Menihi range—Continued.

Ore.	Iron.	Phosphorus.	Silica.	Manganese.	Alumina.	Lime.	Magnesia.	Sulphur.	Loss by ignition.	Moisture.
Sauntry No. 1 (Sauntry mine)	61.68	0.053	5.94	0.50	1.88	0.21	0.11	0.006	.....	.....
	56.221	.0483	5.414	.455	1.713	.191	.100	.0054	.....	8.85
Sauntry No. 2 (Sauntry mine)	61.64	.079	6.03	.80	2.07	.29	.11	.005	.....	.....
	56.184	.0720	5.496	.729	1.886	.264	.102	.0045	.....	8.85
Shilling (Biwabik mine)	62.17	.062	2.78	.53	1.06	.22	.07	.013	6.09	.....
	55.25	.055	2.47	.47	.942	.195	.06	.011	5.41	11.13
Sparta (Sparta mine)	61.63	.025	7.75	.40	.69	.15	.26	.019	2.35	.....
	56.3288	.02285	7.0835	.3656	.6307	.1371	.2376	.0174	2.1479	8.60
Stephens (Stephens mine)	60.00	.070	3.75	.....	.....	.....	.....	.....	.....	.....
	54.000	.0630	3.375	.....	.....	.....	.....	.....	.....	10.00
Stesse (Biwabik mine)	62.64	.037	2.48	1.07	1.22	.12	.05	.007	4.87	.....
	57.86	.034	2.29	.988	1.127	.11	.046	.006	4.498	7.62
Stevenson (Stevenson mine)	64.890	.036	3.020	.310	.720	.260	.180	.005	2.720	.....
	59.504	.033	2.769	.284	.660	.238	.165	.004	2.494	8.300
Thompson (Spruce mine)	63.01	.036	3.34	.607	.82	.185	.113	.027	4.06	.....
	55.000	.0317	2.947	.5356	.723	.1592	.0997	.0238	4.111	11.76
Top Brown (Sparta mine)	60.99	.066	5.30	.88	.95	.15	.24	.018	4.43	.....
	54.8788	.05939	4.7689	.7918	.8548	.1350	.2160	.0162	3.9861	10.02
Tubal (Lake Superior mines)	61.19	.060	4.45	.938	2.57	.168	.062	.016	4.18	.....
	52.953	.0519	3.851	.8117	2.224	.1453	.0536	.0138	3.617	13.46
Union (Union mine)	60.54	.041	.....	.....	.....	.....	.....	.....	.....	.....
	55.63	.0376	.....	.....	.....	.....	.....	.....	.....	8.11
Wallace (Stevenson mine)	64.850	.055	2.100	.370	.900	.180	.210	.008	2.900	.....
	58.559	.049	1.896	.334	.812	.162	.189	.007	2.618	9.700
Welsh (Fayal mine)	61.45	.055	3.35	.61	1.07	.47	.24	.016	5.79	.....
	54.432	.0487	2.927	.540	.947	.416	.212	.0141	5.128	11.42

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The above figures show that the Mesabi ores at present mined contain a high percentage of iron—indeed, a higher percentage than is shown by the average of all the ores mined in the other ranges of the Lake Superior region. At the present time ore containing less than 58 per cent is not mined on the Mesabi, except in small quantity for mixing with higher grades, thus making the cargo grade above 58 per cent.

The slightly hydrated hematites make up the bulk of the ore shipped from the Mesabi range, and therefore their average composition is approximately that given above for the entire Mesabi shipment.

The percentage of iron in the yellow or brown ores averages less than the figures given for the hematites. Fifty-six to 60 per cent are characteristic figures.

The loss on ignition, above shown, is presumably largely combined water. However, this may not represent all the combined water, for the ores are dried at 212° F., and it is extremely likely that at this temperature some of the combined water is driven off. Where Mesabi ore has been finely powdered and dried for a longer time than usual a half to 1 per cent more of water has been lost by this drying.[a] Again, there may be a really greater loss of combined water on ignition than is shown by the weight, because there is an actual gain of weight due to the oxidation of a ferrous oxide to a ferric oxide. On the other hand, the loss on ignition may be partly due to the burning of organic matter, or to the conversion of a carbonate to an oxide, or to the decomposition of a sulphide whereby the sulphur is eliminated. But while the average of 3 per cent is perhaps a trifle low, the figure probably represents nearly the average conditions. From these average conditions there are wide variations, for it is known that some of the yellow ores are highly hydrated, while others are slightly so. For instance, some of the "yellow ocher" in the Biwabik group of mines showed an average content of water, according to H. V. Winchell, of 10.1 per cent, thus being goethite.

The wide variation in moisture driven off at 212°—that is, hygroscopic water—is due to the character of the ore and to local conditions. A porous ore is likely to contain more free water than a dense ore. An ore which has been standing in water is likely to contain more free water than ores which have been in drier places. In the Mountain Iron deposit the content

[a] As per letter of R. B. Green, chemist, Minnesota Iron Co., dated March 4, 1902.

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of free water varies from 6 per cent at the top of the open cut to 15 per cent at the bottom, and all is above ground water. When mines are first opened up the content of water is usually larger than later when the mine has been partially drained. A heavy rainstorm also will make a difference of 2 or 3 per cent in the total.

Only two deposits on the range are known to contain sulphur in injurious amounts. The sulphur is present in the form of iron pyrites and is usually confined to the edges of the deposits. In mining these parts of the deposits are simply passed by. The hydrous ores perhaps run a little higher in sulphur than the nonhydrous ores.

The great variation in silica is due to the fact that the iron ore grades into ferruginous chert. Rocks can be obtained showing all percentages of iron and silica, but those containing a sufficient amount of iron to be ranked as ores seldom contain over 8 per cent of silica. In the western portions of the range the silica content is on an average higher than in the central portion, and in some deposits is so high as to run the percentage of iron down below the salable limit.

The variation in alumina is due to the varying content of clayey and slaty material. In general the alumina is a trifle higher in the yellow ores than in the blue or black ores, although there are exceptions. This appears in comparing the higher and lower grades of ore in the preceding table. Throughout the district the lower grades of ore are the ones which are likely to contain more of the yellow ore than the remainder of the ores. For instance, in comparing the Mountain, Oliver, Juniata, and Preble grades of ore from the Mountain Iron mine it appears that as the iron runs down the alumina runs up. The paint rocks uniformly contain a much higher percentage of alumina than any other rock in the iron formation.

As phosphorus in considerable quantity prevents use of ores for the acid Bessemer process, the phosphorus content in an ore is of the greatest importance. The Bessemer limit is vague, but is commonly placed at 0.045 to 0.050 in phosphorus. From 60 to 70 per cent of Mesabi ores would be ranked as Bessemer. However, ores containing a much higher percentage of phosphorus are used in quantity in basic open-hearth furnaces, and with the rapid growth of the open-hearth method of steel making such ores will be in even greater demand.

In the little hydrated hematites the phosphorus is below 0.05 per cent,

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although occasionally running a little higher. In the hydrous ores the average of the phosphorus is higher. The common figures are above 0.05 per cent. It is not necessary to give detailed figures for particular ores. Chemists, mining engineers, and mine managers all agree to this. As the hydrous ores are, on the whole, more abundant in the upper portion of the deposits than elsewhere, the phosphorus is correspondingly more abundant at this horizon.

It will be seen below that the Mesabi ore is partly in the form of soft dirt and partly in hard lumps. To ascertain whether or not there is any difference in the percentage of phosphorus in the hard and soft lumps, in order to regulate the sampling, Mr. R. B. Green, of the Minnesota Iron Company, made a considerable number of analyses from cargoes of Canton, Norman, and Fayal ores, with results as follows:

Percentage of phosphorus in hard and soft lumps of ores.

Lump.	Fine.
0.046	0.033
.043	.032
.048	.053
.045	.048
.059	.067
.072	.059
.064	.050
.041	.037
.047	.036
.0517 (Average)	.046

These figures indicate in general a slightly higher percentage of phosphorus in the hard lumps than in the soft ones. A similar result was obtained by Mr. E. T. Griese in comparing the hard and soft lumps of the Biwabik mine. The soft material ran below 0.035, while the harder lumps ran up to 0.040 to 0.050.

Ores containing over 1½ per cent of manganese are shipped only to a small extent. However, there are present in the Mesabi district ores containing a considerable higher percentage of manganese. In the Mountain Iron, the Moose, and the Oliver deposits bunches of ore have been found to run locally from 15 to 61 per cent in manganese. The Oliver property is the only one on the range containing sufficient amount of manganese to prevent the shipment of any considerable proportion of its ore. Attempts have been made to utilize such ores as a manganese ore,

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but thus far without success. In the samples of hard and soft material analyzed by Mr. Green it was found that the manganese was slightly higher in the hard lumps than in the soft ones. A similar result was obtained by Mr. Gordon of the Mountain Iron mine, as a result of analyses of Mountain Iron and Oliver ores. In the Biwabik mine the hard ore there found runs distinctly higher in manganese than the soft ore. Finally, certain of the yellow ores run as high as 1 per cent of manganese, while the blue and black ores seldom go over 0.50 per cent, except when close to the wall rock.

Analyses of magnetite from the eastward continuation of the Mesabi, in the neighborhood of Akeley and Gunflint lakes, are as follows:

Analyses of magnetite from neighborhood of Akeley and Gunflint lakes.

Constituent.	1.	2.	3.	4.
Fe	58.40	54.01	63.98	61.95
Fe_3O_4				85.55
SiO_2	8.22	9.37	8.90	11.39
Al_2O_3	.52	.07		Trace.
CaO				.22
MgO				3.44
P	.36	.32	.28	.02
Mn	4.92	5.02	None.	
Ti	None.	None.	Trace.	None.
S				Trace.

1, 2, and 3. (Average of 6 samples). From NE. ¼ of NE. ¼ sec. 29, T. 65 N., R. 4 W. (west end of Gunflint Lake). Analysis by Rattle and Nye, Cleveland. Published by N. H. Winchell, Geol. Nat. Hist. Survey Minnesota, Bull. No. 6.

4. From SE. ¼ sec. 30, T. 62 N., R. 10 W. (transported masses of gabbro). Analysis by C. F. Sidener. Published by N. H. Winchell, Geol. Nat. Hist. Survey Minnesota, Bull. No. 6.

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The magnetites at the east end of the range have not yet been found in paying quantities. Analyses of magnetite from ranges 12 and 13 are as follows:

Analyses of magnetite from ranges 12 and 13.

Constituent.	1.	2.
SiO_2	1.16	11.89
Al_2O_3	1.81	.34
Fe_2O_3	69.08	.....
Fe_3O_4	.....	87.00
FeO	27.10	.....
Fe	69.43	63.07
MgO	.25	.80
CaO	0.53	0.20
TiO_2	None.	None.
P_2O_5	.06	.....
P	.....	.056
MnO	.33	.....
S	.....	Trace.

1. From the east end of Mesabi, SE. ¼ of SE. ¼ sec. 34, T. 61 N., R. 12 W. Analysis by W. H. Melville, for W. S. Bayley.

2. From the NE. ¼ of sec. 23, T. 60 N., R. 13 W. (near Iron Lake). Analysis by C. F. Sidener. Published by N. H. Winchell, Geol. Nat. Hist. Survey Minnesota, Bull. No. 6.

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It will be noted that the magnetites contain little or no titanium. In this they differ from the magnetites occurring in the gabbro. Analysis of the latter are as follows:

Analyses of magnetites in gabbro.

Constituent.	1.	2.	3.
SiO_2	20.90	2.02	11.37
Al_2O_3	1.75	2.68	1.32
CaO	Trace.	Trace.	.10
MgO	2.63	.....	2.73
TiO_2	2.23	.....	16.03
P	None.	.....	.01
P_2O_5	.....	.03	.....
FeO	2.01	.....	14.42
Fe_2O_3	70.29	80.78	53.33
Fe	52.46	58.48	49.40
Ti	.....	12.09	.....
Cr_2O_3	.....	2.40	.....
S	.....	.....	Trace.

1. From the neighborhood of Iron Lake in T. 65 N., R. 3 W. Analysis by Prof. J. A. Dodge. Published by N. H. Winchell, Geol. Nat. Hist. Survey Minnesota, Bull. No. 6.

2. From SE. ¼ sec. 36, T. 65 N., R. 3 W. (Iron Lake). Analysis by R. S. Robertson, Pittsburg. Published by N. H. Winchell, Geol. Nat. Hist. Survey Minnesota, Bull. No. 6.

3. From sec. 36, T. 63 N., R. 10 W. Analysis by C. F. Sidener. Published by N. H. Winchell, Geol. Nat. Hist. Survey Minnesota, Bull. No. 6.

The paint rock frequently associated with ore deposits has a much lower average content of iron than either the hematite or hydrous ores. It averages all the way from 12 to 45 per cent or even to 55 per cent. Figures between 40 and 50 per cent are the most common ones. Phosphorus is also usually but not invariably high. The usual range is from 0.070 to 0.150. Alumina is also much higher in the paint rock than in the hematite or hydrous ores. The figures run as high as 7 per cent (Lerch); 3 to 4 per cent (Griese) may be the average. The water content is characteristically large.

TEXTURE AND STRUCTURE.

The Mesabi ores range in texture from large crystalline masses requiring the use of a crusher, as at Biwabik, to fine, soft dirt, which runs like dust between the fingers. In general the ores at Virginia and Eveleth and eastward are somewhat harder and coarser than those of Mountain

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Iron, Hibbing, and vicinity, although there are exceptions both ways. The deposits are thin, bedded in layers varying from a fraction of an inch to several inches, or even feet. Usually some of the layers are soft and pulverulent while others are more or less hard and broken up into small parallelopiped blocks by cross fractures. The best physical texture for furnace purposes, a medium hard ore in small lumps, is frequently found along the edges of the deposits. A stroke of the pick at almost any point in a deposit will loosen a mass of soft ore mixed with small blocks of hard ore which seldom exceed a few inches in length and breadth. The average texture of some of the ores is shown by the following screening figures of representative ores kindly furnished by Mr. R. B. Green, chemist of the Minnesota Iron Company:

Average texture of ore.

	Ore not passing through a screen with 8 meshes to the inch.[a]	Ore passing through screen with 8 meshes to the inch.	Ore passing through screen with 20 meshes to the inch.	Ore passing through screen with 100 meshes to the inch.
1898.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
Audrey ore, Auburn mine (41 cargoes)	60.88	9.52	18.72	10.88
Auburn ore, Auburn mine (13 cargoes)	51.73	7.96	20.38	19.92
Fayal ore (43 cargoes)	72.17	8.42	15.93	3.48
Genoa ore (34 cargoes)	71.47	7.09	18.42	3.01
Sparta ore (44 cargoes)	65.71	5.58	15.64	13.09
Elba ore (6 cargoes)	64.13	6.96	20.05	8.80
1901.				
Norman ore (23 cargoes)	59.38	6.79	18.16	15.66
Top Brown, Sparta mine (8 cargoes)	64.92	6.92	16.42	11.74
Vulcan ore, Spruce mine (18 cargoes)	65.92	5.85	15.35	12.88
Mountain Iron ore	75 to 80	75 to 80	75 to 80	20 to 25

[a] Determined in natural state after taking from cars and drying.

The looseness of the ore as it lies in the deposit is shown by the fact that in computing the tonnage of Mesabi ores 11½ to 14, or rarely even 17 to 18, cubic feet are allowed per long ton (2,240 pounds), whereas in the hard-ore deposits of other ranges the common figures are 8 or 9 cubic feet.

If the ore were all limonite with a specific gravity of 3.6, and if a ton be supposed to occupy 14 cubic feet, the calculated pore space would be 29 per cent. If the ore were all hematite with a specific gravity approaching 5, the pore space would be 48 per cent. If a ton of ore be supposed to

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occupy 11½ cubic feet, there would be 13 per cent pore space if it were limonite and 38 per cent if it were hematite. As the ore is an intermediate variety between hematite and limonite, it is probable that the average pore space is somewhere in the neighborhood of 35 per cent, though locally showing wide variations. In contrast to this the pore space in the old range ores is commonly less than 20 per cent.

The bedded structure of the Mesabi ore deposits is a striking feature. A single bed commonly shows much persistence in color and texture where followed out laterally, but differs in these particulars from beds above and below, with the result that the bedding structure is made most conspicuous. (See Pls. XXIV to XXXIII.) White and colored efflorescence along the bedding still further emphasizes it. The bedding planes in general pitch gently, perhaps 8° to 20°, toward the lower end of the basin in which they lie. The beds may also dip gently from the side of the channel in toward its axis, as in the Oliver mine, or may have a monoclinal tilt, as in the Hale and Kanawha mines. (See Pl. XXXIII.) In exceptional instances dips are as high as 50° to 60°, as at the Stephenson, Sauntry-Alpena, Sparta, and Kanawha mines. Close to the wall rocks of the deposits the dip of the beds of ore usually becomes suddenly steeper and may jump up 45° or more at the immediate contact. Besides having the above general attitudes the iron-formation layers are much contorted in a minor way. In walking through any of the open pits of the mines the gentle minor undulations of the layers are everywhere apparent, and here and there folds of unusual sharpness stand out conspicuously.

Some of the dips observed in the Mountain Iron mine are as follows:

Dips observed in Mountain Iron mine.

AT LOWEST LEVEL ON EAST SIDE OF PIT GOING SOUTH.

8° S.	30° SSW.	8° S.	20° N.
1° S.	6° S.	5° NW.	2° E.
5° S.	4° N.	10° NNE.	0°.
10° SSW.	4° N.	6° S.	11° SE.
7° SE.	9° N.	22° S.	
3° S.	8° S.	35° N.	

AT SECOND LEVEL ON EAST SIDE OF PIT GOING NORTH.

19° SE.	40° SE.	6° NW.	20° SW.
3° NW.	6° E.	0°.	8° SE.
5° NNW.	39° SSW.	6° NW.	15° W.
11° S.	44° SSW.	5° NW.	20° W.
20° SE.	4° E.	7° SW.	

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Dips in the Oliver mine at Virginia are as follows:

Dips in Oliver mine.

GOING NORTH TO MIDDLE OF PIT.

9° NW.	7° NW.		

ACROSS SYNCLINE AT UPPER END OF PIT FROM SOUTH TO NORTH.

21° NE.	9° NE.	19° SW.	

GOING WEST ALONG NORTH WALL.

12° SSW.	30° SSW.	15° W.	40° SSW.
35° SSW.	20° SSW.		

Dips in the Biwabik mine, beginning at east end of mine and running along the north wall on the upper level, are as follows:

Dips in Biwabik mine.

28° S.	15° W.	12° S.	14° S.
18° SSW.	13° SSW.	10° S.	12° S.
16° WSW.	14° S.	17° S.	
19° SW.	20° S.	20° SSW.	

The bedding, while in general roughly parallel to the surface, in some deposits shows discordance with the surface. In the Sauntry mine, for instance, the surface of the deposit may be observed to cut diagonally across the layers of the ore deposit.

Nodules of iron ore are frequently found with their greater diameters parallel to the bedding. The nodules vary from a fraction of an inch up to 6 or 8 inches or more in size. They are frequently hollow and sometimes show concentric arrangement of hydrated and nonhydrated ores.

In addition to the bedded and folded structures, the ore deposits show many fractures, especially along the contact with the wall rock. The individual layers, where hard enough, are broken into small blocks by fractures which in the main are independent of those in the layers above and below. Also numerous joints and faults cut across the ore deposit. Indeed, in some deposits there is scarcely a cubic yard which is not crossed by one or more such fractures. For the most part there is little displacement along fractures, and where displacement does occur it is measured by inches rather than feet. Rarely a fault of several feet may be observed, and this is likely to be near the contact of the ore with the wall rock.

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The numerous joints and faults suggest that the apparent gentle folds in the iron-bearing strata are not due entirely to actual bending of the strata, but are due in part to minute displacement along the closely spaced fractures.

THE ROCKS FORMING THE BOTTOMS AND SIDES OF THE ORE DEPOSITS.

The rocks adjacent to the Mesabi iron-bearing deposits are ferruginous cherts, more particularly the altered varieties, ferruginous slates, paint rocks, and even unaltered slates. In abundance the rocks stand in the order named. In one mine, the Hale, the north wall of the ore deposit is a micaceous phase of the Pokegama quartzite associated with a schistose Archean basalt. The north wall of the Biwabik mine also may be quartzite, although exploitation has not yet shown this. The conditions in these two mines are exceptional.

STRUCTURAL RELATIONS OF THE ORES TO THE ADJACENT ROCKS.

The shape of the ore deposits and the attitude of their layers can be easily made out from the mining and exploration work done on them. But it is difficult to make positive statements as to the structural relations of the Mesabi iron ores to the adjacent rocks for the reason that a very small proportion of the deposits of the range have been exploited to a sufficient extent to show such relations. Many deposits have not been opened up at all, and the preliminary exploration does not reveal information of this sort. In the underground mining the drifts reach the wall rock in too few places to warrant general statements as to the structure. Most of the open cuts also have as yet either not reached the wall rock at all or have reached it only on one side. Assembling all the data available concerning the relations of the ore to the wall rock, the following general statements seem to be warranted:

(1) In a few mines, as for instance the Oliver, the layers of rock adjacent to the ore have such attitudes as to show the ore to lie near the axis of a gently pitching trough formed by the folding of the rock layers.

The ore deposits of this class have relations, which are expressed in fig. 9. On each side the wall rocks dip in toward the ore deposit. The upper layers abut against the ore deposit. The lower layers form a gentle trough beneath, which usually has many minor undulations. The iron-ore

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beds themselves are bowed into a gentle trough more or less complex, with slopes similar to those of the rock layers below and at the sides. In other words, the layers of the ore deposit and the layers of the rock *together* make up a gentle syncline, with even slopes. This does not mean that the slopes of the bottom of the deposit are gentle and even. Indeed, the surface of the contact of the rock and ore is exceedingly irregular, as already noted, and usually terraced, and the dip of the contact surface is usually steeper than the dip of the strata. In other words, the bottom of the deposit forms a trough with much more irregular bottom and much steeper slopes at the sides than the trough formed by the bowing of the strata of the iron formation and ore deposit together.

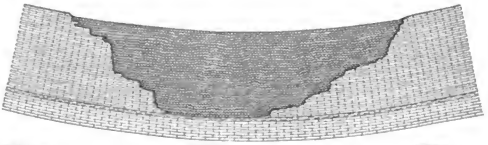

FIG. 9.—Ideal cross section of a Mesabi ore deposit showing relations to ferruginous chert and impervious slate layers.

The longer directions of the ore deposit in such cases are usually parallel to the axis of the trough.

(2) The rock layers about other ore deposits form pitching troughs, but the folding is so slight that the pitch is far more conspicuous than the dip of the limbs, and in this case the rock layers on all sides of the deposit have essentially a monoclinal attitude. The longer direction of the deposit may be either parallel or transverse to the monoclinal pitch, but it is usually transverse. The Canton, Biwabik (Pl. XXXII), Cincinnati, and Sauntry (Pl. XXXI) mines are instances of this.

(3) About still other deposits the rock layers show no traces of synclinal flexure, and the dip is essentially monoclinal with minor variations in degree. It is not unlikely in some cases that the layers, while essentially monoclinal, are even slightly bowed into anticlines. The deposit in this case lies on the limb of one of the gentle folds into which

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the iron formation is flexed, either the great major fold or one of the minor cross folds giving the gentle tilting of the iron formation to the south. Instances of such relations appear at Hale (Pl. XXXIII), Kanawha, and Sparta mines. The longer direction of the deposit is nearly always transverse to the pitch.

A generalized cross section of a Mesabi ore deposit parallel to the pitch of the fold or parallel to the dip of the monoclinal rock strata is shown in fig. 10.

In general it is likely that more of the ore is to be found in structural synclines in the iron formation than elsewhere, but this may not be in all cases apparent in the attitude of the layers immediately adjacent to the ore deposit, for the ore deposit may fill only a very small portion of a broad and gentle syncline, or be one of several deposits in such a syncline, and

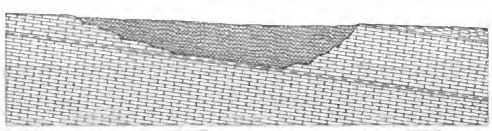

FIG. 10.—Ideal section parallel to the pitch of a Mesabi ore deposit, showing relations to ferruginous chert and to impervious slate layer.

the minor structure of the iron-formation layers immediately adjacent to the ores may give no evidence of the existence of the major syncline in the iron-formation layers. These structural relations are explained in connection with the discussion of the origin of the ores, where it is shown that the ores have been concentrated through the agency of underground waters working their way through a gently folded and much fractured formation, in which the major flow of water has been directed by the broad gentle synclines in the iron formation, but in which the cross fractures have locally concentrated the circulation and given it most capricious turns.

The structural relations of the ore to the wall rock at the immediate contact in the above cases may be any of the following:

(1) The layers of the wall rock may grade into the layers of the ore without change of dip. (Pl. XX, fig. *B*.) This is likely to be observed at the contact of the ore with horses of rock or islands of rock within the ore.

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(2) The layers of the wall rock may grade into the layers of the ore, and at the contact there is a sharp downward deflection of the ore layers. (Pl. XX, fig. *A*.) The layers of the ore may be almost perpendicular, and dips of 45° are common. Within a few feet, or at least a few yards, the layers of the ore deposit take on their usual gentle dip.

(3) Accompanying the downward flexure of the ore layers there may be jointing, faulting, or brecciation. Where the flexures of the layers pass into fractures, the displacement is usually small, a few inches or at most a few feet. In certain mines the displacement between the ore and the wall rock may have been greater, although decisive evidence is lacking. The steep walls to be seen in some deposits, as, for instance, the Oliver, Elba, and Canton, have sometimes been taken as evidence of extensive faulting. While the walls are steep as compared with the average of the wall-rock slopes on the range, in detail they are terraced, some of the terraces running out 20 feet or more. It is apparent that there has not been any great displacement parallel to the wall, for the terraces would have required a tremendous local disturbance of the ore close to the contact during the movement, and this does not appear. North of the Biwabik mine in the NW. ¼ of NW. ¼ sec. 2, T. 58 N., R. 16 W., a pit has been sunk 70 feet in ore just 60 feet south of a pit showing Pokegama quartzite. If the quartzite passes under the ore, it must do so with a dip of over 45°, a dip much greater than the average in the Upper Huronian, although such dips are indeed to be observed. The quartzite is much broken up and disintegrated here, and it is not impossible that we have here a fault with a considerable displacement. At the Hale and Kanawha mines the open cuts show the north wall to be the green rock of the Archean, with thin films of micaceous Pokegama quartzite and iron formation adhering to it. The vertical and lateral dimensions of the deposit parallel to the wall are greater than that normal to it, and the dip of the iron formation and ore strata is steep, being in some places as high as 60° to the south. (See Pl. XXXIII.) The attitude and steep dip of the deposit are in accord with the idea that it has been developed in a plane of weakness along the contact at the Archean and Upper Huronian, where there has been considerable movement, but there is no direct evidence of this.

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PLATE XX.

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PLATE XX.

VIEWS OF THE CONTACT OF ORE WITH WALL ROCK IN THE BIWABIK AND MOUNTAIN IRON MINES.

FIG. *A*.—This view is taken from the west end of the Biwabik mine. The strata on the left side of the picture are ferruginous chert, and those on the right side are ore. The fairly sharp downward bend of the strata from left to right near the center of the field is at the contact of the ore and ferruginous chert. The layers of the ferruginous chert are, for the most part, directly continuous with, and grade into, the layers of ore, the gradation being accomplished within a few feet. The flexure at the contact is due to the slumping down of the ore layers, which is caused by abstraction of silica in solution, as explained on page 262. This is a characteristic feature at the contact of the ore and wall rock in most deposits on the range.

FIG. *B*.—This view shows a contact of the ore and the ferruginous chert forming the wall rock in the south railway approach of the Mountain Iron mine. The upper strata, appearing lighter colored and more coarsely bedded than the lower, are ferruginous chert; the lower fine-bedded strata are iron ore. The rock forms a thin shelf projecting over and into the ore deposit at this point. The layers of ore at the south end of the mine grade directly without any disturbance into layers of ferruginous chert forming the wall rock; the layers of ore and rock are strictly parallel. Near the contact they become interleaved, layers of ore extending well into the wall rock, and, vice versa, layers of wall rock extending well into the ore.

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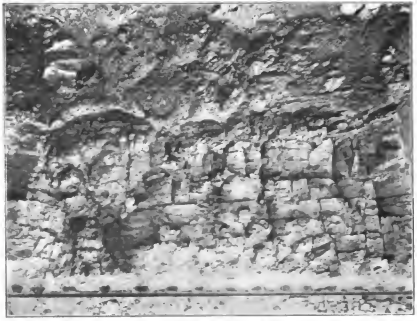
A. CONTACT OF ORE WITH WALL ROCK IN BIWABIK MINE



B. CONTACT OF ORE WITH WALL ROCK IN MOUNTAIN IRON MINE

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Virginia slate. The equivalence of the paint rock and slate is indicated by the actual transition to be observed at a number of cases, and also by their structural relations. The sump of the pump shaft of the Penobscot mine is bottomed in slate under 298 feet of ferruginous chert. At the bottom of the adjacent ore deposit at the same horizon is a zone of paint rock. In the Biwabik mine there is a capping of paint rock. East and west along the strike of the paint rock there is found black slate. Also a well driven in the paint rock and ore 600 feet south of the southernmost pit pierces typical black slate at a depth which ought to show paint rock if the paint rock continues southward with approximately the dip it shows in the mine.

At the bottom of the deposit the ore is usually in sharp contact with ferruginous chert, with practically no gradation, but paint rock is also frequently found immediately underlying the ore. This may be in single thin seams a fraction of an inch or several inches in thickness, or may be in several thin layers interleaved with the ore in a zone several feet thick. Beneath the paint rock, and to a certain extent mixed in with it, is some variety of ferruginous chert or ferruginous slate, principally the former. Toward the sides of the channels the paint rock between the ore and the ferruginous chert becomes less abundant or altogether disappears, and the ore rests directly upon the ferruginous chert. Attention has been called to the fact that the sides of the trough are in a series of steps. On these steps there is seldom any paint rock separating the ferruginous chert from the ore.

DRAINAGE.

Because of the bedded and jointed structure of the ore deposits water is able to pass through them freely. Water probably flows along the beds more freely than across them, for the bedding partings present more continuous openings than the joints, which in the ore deposits are irregular and discontinuous, and frequently cut off by soft impervious layers, which have yielded to deformation by bending rather than by jointing, and, moreover, certain layers—for instance, limonite layers—are themselves very porous. Locally, however, the flowage along joints is dominant.

The ore deposits are at present in part above water level and in part below. On the upper slopes the deposits are largely above water level, on the lower slopes below water level, although there are many exceptions to

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both. Thus it is that certain mines are comparatively dry throughout the year while others are permanently wet. A good instance of this appears at Virginia, where the Columbia mine on low ground receives a vast quantity of water while the mines on high ground adjacent are comparatively dry. The pumping of vast quantities of water from mines below the level of ground water has materially reduced the general level of ground water in this and adjacent areas. The Penobscot mine, for instance, discharges in the neighborhood of 5,000 gallons per minute, and thereby drains the mines to the north and west. The cessation of pumping at the Penobscot mine would immediately raise the level of ground water in the adjacent mines were pumping not begun in them. At the Biwabik mine the level has been lowered from 75 feet below the surface to 150 feet below the surface. Below the level of ground water the amount of water to be handled in the deposits varies with the depth below the level because of the increased head and increased contributing area in the shafts. Many mines show increased flow toward the bottom. Before any artificial openings were driven into the ore deposits the flowage along the bottom may not have been any greater than, if indeed so great, as in upper portions, as shown by fig. 11, described in Chapter IX. The outlet for the water was then at a higher level, near the surface of the formation.

Above the level of ground water the ore contains water, but is not saturated. In this zone the amount of water in the ore increases from the top down. In the Mountain Iron mine the amount of hygroscopic moisture in the ore is said by A. T. Gordon, chemist in the mine, to vary from 6 per cent in the upper part of the deposit to 15 per cent in the lower part. During periods of great precipitation the amount of water in the deposits above the level of ground water is increased and at such times also the level of ground water is raised. Where mine openings have been made above the level of ground water the amount of water contributed to the openings during such periods is of course increased.

Many deposits in the range, though not all by any means, lie under surface depressions or surface drainage channels, due to development in original rock synclines, as shown on a subsequent page, or to gouging out by erosion to a greater extent than the adjacent harder rocks. Glacial drift has tended to obscure these rock depressions, and does so completely in many places. Where open cuts have been made in deposits under-

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lying such drainage basins great precautions have to be taken to guard agains flooding from this surface drainage. In 1900 the Mountain Iron open cut, which by pumping is ordinarily kept above the level of ground water, received 70,000,000 gallons of water in a few hours. At the same time the Fayal mine fared nearly as badly. The extensive drainage ditches to be seen about the open pits testify to the tendency for increased flow at such times.

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CHAPTER IX.

ORIGIN OF THE IRON ORES.

GENERAL STATEMENT.

The iron ores have come chiefly from the alteration of rocks made up of minute granules of green hydrated ferrous silicate, which we have called greenalite (see pp. 101–115 and Pls. VIII, IX, and XIII). A small part of the ore has resulted from the alteration of siderite. The proof of the development of the ores from greenalite is, briefly, as follows:

1. All stages of the alteration from the fresh greenalite granules to the other phases of the iron formation, including the ores, are to be observed.

2. Much of the ore and associated rocks show traces of the greenalite granules. The granules may be represented by iron oxide, by chert, by actinolite or grünerite, by unaltered greenalite, by any combination of these substances, or by any gradation phase between them.

3. Greenalite is one of the less stable of the iron-formation materials, and its alterations to the other phases of the iron formation would be chemically characteristic of conditions under which the iron formation has existed during the concentration of the ore. The reverse change would not be probable under such conditions. Greenalite is found in parts of the iron formation which have suffered the least alteration; i. e., in association with slate layers in the iron formation or just below the Virginia slate.

The proof of the development of a small portion of the ore from siderite is, briefly, as follows: Associated with the greenalite and slaty layers in the least-altered portions of the iron formation are thin layers of iron carbonate, some of which, from interlamination with the easily soluble greenalite, probably is original and not the product of alteration of greenalite. Near Birch Lake undoubted fine-banded original carbonate is found. If iron carbonate is now found in the unaltered portions of the iron formation, it must have originally occurred in the more altered portions. Its alteration to the other phases of the iron formation now

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observed would be chemically characteristic of the conditions under which the iron formation has existed. Certain of the finely banded ores—as, for instance, some of those at the Mountain Iron mine—may have thus resulted, although there is no evidence in the ores themselves, aside from their fine banding, suggestive of development from banded carbonate. The fact that the ores of the Penokee-Gogebic range have been proved mainly to develop from iron carbonate further suggests the probability of such a change having occurred.

The development of the iron ores from greenalite has consisted in the breaking up of the greenalite into its constituents—mainly protoxide of iron (FeO), silica (SiO_2), water (H_2O)—the partial or complete oxidation and hydration of the protoxide of iron, and the abstraction of the silica, probably much of it as colloidal silicic acid (H_4SiO_4), in solution. Where the original rock was siderite the development of the ores occurred in a similar way. It consisted in the breaking up of the siderite into ferrous iron and carbon dioxide, the partial or complete oxidation and hydration of the protoxide of iron, and the abstraction of carbon dioxide as carbonic acid in solution.

Where the oxidation has been complete, the sesquioxides have developed; these are usually somewhat hydrated. Where the oxidation has been partial, magnetite has developed.

The derivation of the iron ores from greenalite and siderite has been brought about through the agency of surface weathering and of waters percolating through the formation both above and below the level of ground water. This is shown by the nature of the chemical changes which the ore and associated rocks of the iron formation give evidence of having undergone, by the fact that the silica and iron have been transported and rearranged and the silica largely abstracted from what are now the ore bodies, by the frequent occurrence of the ore in nodules and in stalactitic forms in cavities, by the occurrence of the ore in underground drainage channels in the iron formation, and finally by the fact that water may now be observed coursing through the formation bearing mineral constituents indicative of such changes.

The greenalite rock itself is a sedimentary oceanic deposit, as shown by its bedded character and its interstratification and conformity with ordinary slate and quartzite. Its development is believed to be both by chemical and organic processes.

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The above general outline of the genesis of the iron-ore deposits is filled in below. The development will be described in the order of sequence of events, and the first subject to be considered in detail is naturally the origin of the greenalite granules.

ORIGIN OF THE GREENALITE GRANULES.

GREENALITE A SEDIMENTARY DEPOSIT.

The rocks containing greenalite grade into quartzite below, into slate above, into slate laterally, and contain interstratified slate layers. They show bedding which is strictly conformable to that of the associated sedimentary rocks. There is therefore no question that the greenalite of the iron formation is a sedimentary deposit. The occurrence of greenalite or its altered equivalents between quartzite and slate would indicate the conditions of its deposition to be somewhat intermediate between those favorable to sand deposition and those favorable to mud deposition.

SIMILARITY OF GREENALITE TO GLAUCONITE.

Spurr, in his work on the Mesabi range in 1894,[a] noted the similarity of the greenalite granules here described with glauconite, a green silicate of iron and potassium, found in formations of the most various ages and brought up in dredging operations from the sea bottom near the edge of the continental shelf, where it occurs in all stages of development by deposition in the interiors of foraminifera and other organisms, and possibly in small part developed as entoöliths and concretions independently of organisms. In color, size, shape, and optical properties the two substances are almost identical, but in other respects they differ.

Murray and Renard, who have investigated modern glauconite deposits through the dredgings of the *Challenger* expedition, emphasize the characteristic accompaniments of glauconite. "Glauconite is almost always accompanied by quartz, orthoclase (often kaolinized), white mica, plagioclase, hornblende, magnetite, garnet, epidote, tourmaline, zircon, and fragments of ancient rocks, such as gneiss, mica-schists, chlorite rocks, granite, diabase, etc. In addition to these minerals, there seems always to be associated with glauconite, in modern deposits, a considerable quantity of organic matter, often apparently of a vegetable nature. The glauconitic

[a] Geol. Nat. Hist. Survey Minnesota, Bull. No. 10.

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grains frequently contain traces of phosphate of lime and make up a considerable part of some phosphatic nodules, so that phosphate of lime may be said to be one of its constant accompaniments."[a] No trace of these substances remains in the greenalite deposits under discussion. In thickness of the deposits the glauconite and greenalite deposits differ. The former are nowhere found unmixed with foreign material with a thickness exceeding 35 feet, while the greenalite granules in the Mesabi district have made up a deposit with a thickness of 1,000 feet or more, with only thin layers of mud.

In the fundamental property of composition they are dissimilar. Spurr himself noted this dissimilarity in composition, but in view of the wide variety in composition of glauconite, and the similarity in physical properties, concluded that the material was glauconite. A number of analyses of so-called glauconite or greensand are given below. Some of them are not reliable, but it is scarcely possible to make a satisfactory separation of the good and bad without details as to methods.

Analyses of glauconite.

	SiO_2.	Al_2O_3.	Fe_2O_3.	FeO.	MgO.	CaO.	Na_2O.	K_2O.	H_2O.	MnO.	$MgCO_3$.	$CaCO_3$.	Total.
I	58.17	10.09	.....	18.75	3.37	.....	.....	3.37	6.25	.....	.....	.....	100.00
II	53.46	5.00	.....	21.78	6.21	.....	.....	8.79	4.76	.....	.....	.....	100.00
III	49.10	7.05	23.60	3.25	.....	.....	.....	5.75	10.10	.....	.....	.....	98.85
IV	50.80	6.70	21.80	3.10	4.20	.....	.....	3.10	9.80	.....	.....	.....	99.50
V	48.99	6.40	25.80	4.80	Spur.	0.78	.....	5.18	8.98	.....	.....	.....	100.93
VI	49.40	7.10	20.07	3.80	.....	.....	.....	5.75	12.75	.....	.....	.....	98.87
VII	50.20	1.50	28.10	4.20	.....	.....	.....	5.90	8.60	.....	.....	.....	98.50
VIII	47.60	4.20	21.60	3.00	1.40	2.40	.....	4.60	14.70	.....	.....	.....	99.50
IX	49.50	3.20	22.20	6.80	.....	.....	.....	8.00	9.50	.....	.....	.....	99.20
X	43.60	5.10	32.80	3.00	1.50	.....	.....	5.60	7.70	.....	.....	.....	99.30
XI	46.91	7.04	23.06	2.64	4.40	2.85	0.91	7.31	4.71	.....	.....	.....	99.93
XII	50.62	3.80	21.03	6.03	.....	.....	.....	7.14	9.14	.....	0.57	0.54	99.86
XIII	54.18	7.15	.....	20.16	4.08	.....	.....	7.97	5.74	.....	.....	.....	99.28
XIV	50.42	4.79	19.90	5.96	2.28	3.21	.21	7.87	5.28	.....	.....	.....	99.92
XV	49.09	15.21	10.56	3.06	2.65	.55	1.21	6.05	11.64	.....	.....	.....	100.02
XVI	50.70	19.80	.....	8.60	3.70	.....	.50	8.20	8.50	.....	.....	.....	100.00
XVII	46.58	11.45	.....	20.61	1.27	2.49	.98	6.96	9.66	.....	.....	.....	100.00
XVIII	50.70	13.32	.....	20.10	1.18	1.62	.....	.....	.....	.....	.....	.....	.....
XIX	48.45	6.50	.....	24.31	.....	.....	.....	12.01	8.40	.....	.....	.....	99.47
XX	51.50	6.40	.....	24.30	Trace.	.....	.....	9.96	7.70	.....	.....	.....	99.86

[a] Report of the voyage of H. M. S. *Challenger*, 1873–1876, Deep Sea Deposits, p. 383.

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Analyses of glauconite—Continued.

	SiO_2.	Al_2O_3.	Fe_2O_3.	FeO.	MgO.	CaO.	Na_2O.	K_2O.	H_2O.	MnO.	$MgCO_3$.	$CaCO_3$.	Total.
XXI.....	50.75	6.50	.....	22.14	.....	.....	.....	12.96	7.50	.....	.....	.....	99.85
XXII.....	53.26	3.85	.....	24.15	1.10	1.73	1.60	5.36	10.12	.....	.....	.....	101.17
XXIII.....	57.56	6.56	.....	20.13	1.70	1.04	.....	4.88	8.17	.....	.....	.....	100.04
XXIV.....	58.74	4.71	.....	21.06	1.48	.92	.....	3.26	9.79	.....	.....	.....	99.96
XXV.....	49.42	10.23	16.01	3.00	3.78	.31	.26	7.91	8.08	.....	.....	.....	99.00
XXVI.....	51.24	12.22	13.44	3.06	3.93	.10	.31	7.50	8.20	.....	.....	.....	100.00
XXVII.....	49.76	8.18	16.00	3.77	3.97	.41	.52	7.57	9.82	.....	.....	.....	100.00
XXVIII.....	46.90	4.06	27.09	3.00	.70	.20	1.28	6.16	9.25	.....	.....	.....	99.24
XXIX.....	52.86	7.08	7.20	19.48	2.90	Trace.	Trace.	2.23	8.43	.....	.....	.....	100.18
XXX.....	56.62	12.54	15.63	1.18	2.49	1.69	.80	2.52	6.84	Trace.	.....	.....	100.41
XXXI.....	50.85	8.92	24.40	1.66	3.13	1.26	.25	4.21	5.35	Trace.	.....	.....	100.23
XXXII.....	51.80	8.67	24.21	1.54	3.04	1.27	.25	3.86	5.68	Trace.	.....	.....	100.32
XXXIII.....	55.17	8.12	21.59	1.95	2.83	1.34	.27	3.36	5.76	Trace.	.....	.....	100.39
XXXIV.....	27.74	13.02	39.93	1.76	4.62	1.19	.62	.95	10.85	Trace.	.....	.....	100.68
XXXV.....	48.95	7.66	23.43	1.32	2.97	.57	.98	9.54	4.93	.....	.....	.....	100.35
XXXVI.....	44.75	7.82	22.26	2.36	3.25	.....	.30	9.01	5.16	.....	.....	.....	99.91
XXXVII.....	49.53	5.84	20.06	5.95	2.92	.56	.46	9.31	4.91	.....	.....	.....	99.54
XXXVIII.....	51.00	9.93	18.69	1.98	3.85	.87	.35	7.66	5.83	.....	.....	.....	100.16
XXXIX.....	47.88	14.94	17.13	2.68	2.45	.56	.43	8.04	5.91	.....	.....	.....	100.02
XL.....	42.32	16.51	18.91	2.80	1.74	2.20	.42	7.49	7.48	.....	.....	.....	99.87
XLI.....	41.02	22.19	18.49	2.06	.69	1.96	.38	5.74	7.88	.....	.....	.....	100.41
XLII.....	42.35	21.43	8.17	5.78	1.93	8.37	.43	7.16	4.45	.....	.....	.....	100.07
XLIII.....	47.59	17.99	13.95	3.70	1.80	1.22	.42	7.21	5.27	.....	.....	.....	99.15
XLIV.....	52.96	12.76	13.56	2.34	4.11	.....	.47	8.69	4.91	.....	.....	.....	100.10

I. Greensand, from Böderich, between Unna and Werl. Decheu, Nat.-hist. Ver. Bonn, 1855, Vol. XII, p. 176.

II. Greensand, from Dortmund in the direction of Witten. Marck, Ibid., p. 266.

III. Bindlacher Mountain, near Bayreuth. Haushofer, Journ. pr. Chem., 1866, Vol. XCVII, p. 353.

IV. Sorg, near Kronach in Oberfranken. Ibid.

V. Ortenburg, near Passau. Ibid.

VI. Reding at Cham, in the Oberpfalz. Ibid.

VII. Ebendaher. Ibid.

VIII. Benedictbeuern. Ibid.

IX–X. Kressenberg. Ibid.

XI. Insel Gozzo. Bamberger, Tschermak. Mitth., 1887, p. 271.

XII. Havre. Haushofer, Journ. pr. Chem., 1867, Vol. CII, p. 36.

XIII. Villers sur Mer, Dép. Calvados. Pisani, Choizeaux Min., 1862, p. 542.

XIV. Antwerp. Dewalque, Soc. géol. Belgique, 1874, Vol. II, p. 3.

XV. Ashgrove, near Elgin, in Scotland. F. Heddle, Trans. Roy. Soc. Edinb., 1879, Vol. XXIX, p. 79.

XVI. Island of Orleans, Quebec. Hunt, Geol. of Can., 1863, p. 487.

XVII. Red Bird, Mo. Ibid.

XVIII. Gay Head, Massachusetts. S. L. Dana, Hitchcock's G. R. Mass., 1841, p. 93.

XIX. Cauley's pits, at Woodstown, N. J. Rogers, Geol. Rept. N. J., p. 201–204.

XX. Sculltown, N. J. Ibid.

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XXI. Polk Hill, Burlington County, N. Y. Ibid.
XXII. New Jersey, southeast of Philadelphia. Fisher, Am. Journ. Sci., 1850, Vol. IX, p. 83.
XXIII. Coal Bluff, Alabama. Mallet, Am. Journ. Sci., 1857, Vol. XXIII, p. 181.
XXIV. Gainesville, Ala. Ibid.
XXV. Svir R, Russia. A. Kupffer, J. B. Ch., 1307, 1870.
XXVI. Ontika, Russia. Ibid.
XXVII. Grodno Valley, Russia. Ibid.
XXVIII. Agulhas Bank. Gümbel, Ber. Ak. München, 1886.
XXIX. French Creek, Pennsylvania. Knerr and Schoenfeld, Am. Ch. J., Vol. VI, 1884. p. 412.
XXX–XXXIII. Challenger dredging, lat. 34° 13′ S., long. 151° 38′ E., 410 fathoms.
XXXIV. Challenger dredging, lat. 11° 38′ 15″ S., long. 143° 59′ 38″ E., 135 fathoms.
XXXV. Padi, Gouv. Saratow. K. Glinka, Zeitschr. für Kryst., Vol. XXX, 1899, p. 391.
XXXVI. Nasonovo, Gouv. Smolensk. Ibid.
XXXVII. Ural. Ibid.
XXXVIII. Traktemiroff, Gouv. Kiew. Ibid.
XXXIX. Tschernofskóje, Gouv. Nischni-Novgorod. Ibid.
XL. Karowo, Gouv. Kaluga. Ibid.
XLI. The same, another portion. Ibid.
XLII. Kosolapowo, Gouv. Nischni-Novgorod. Ibid.
XLIII. The same, another portion. Ibid.
XLIV. Udriass in Estland. Ibid.

It is apparent from the above analyses that so-called "glauconite" has a very indefinite and variable composition. In mineralogic text-books and in the work of Murray and Renard on modern glauconite deposits the substance is described as "*probably a mixture.*" Indeed, the variation in composition is so marked as to lead one to suspect that substances of different origin have been included under this term. The main variation is in the iron. In most of the samples the iron is largely in the ferric form, and in the analyses of typical glauconite grains collected by the *Challenger* expedition this is true in each case. Indeed, Sir John Murray, after summarizing the results of their work, makes the statement that "the glauconite now forming on the bottom of the sea is, like the glauconite of geological formations, *a hydrous silicate of potash and of ferric oxide*, containing always variable quantities of alumina, ferrous oxide, magnesia, and often lime." Yet in analyses of so-called glauconites from various geologic formations the ferrous iron is greatly in excess of the ferric iron.

Comparing the analyses of glauconite above listed with those of the green granules of the Mesabi iron formation, the following differences appear:

The amount of alumina in glauconite averages 9 per cent in the above table, while less than 1 per cent is found in the greenalite rocks, and this doubtfully belongs with the greenalite.

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The ferric iron in all of the best analyses of glauconite is in greater percentage than the ferrous iron. In the green granules from the Mesabi district ferric iron is nearly if not quite absent. The percentage of metallic iron in glauconite is on an average lower than that of the green granules of the Mesabi district.

Glauconite contains a small percentage of soda. In the Mesabi granules soda is entirely lacking.

Glauconite contains from 3 to 13 per cent of potassa, and, indeed, in descriptions of glauconite in standard text-books the content of potassa is noted as a characteristic of it. In the green granules from the Mesabi district potassa is entirely lacking, and the granules are so fresh and unaltered as to preclude the idea that this substance was originally present and has been removed.

Prof. F. W. Clarke, chief chemist of the United States Geological Survey, under whose direction the chemical work on the Mesabi green granules was done, kindly makes for publication here the following statement concerning the chemical differences between glauconite and greenalite

THE COMPOSITION OF GLAUCONITE AND GREENALITE.

By F. W. Clarke, *Chief Chemist.*

"A scrutiny of the table of analyses of glauconite compiled by Mr. Leith reveals at first sight a hopeless discordance of data. This is due to the fact that glauconite, as actually observed and analyzed, is never pure and definite, but contains a variety of undetermined substances commingled with the true glauconite silicate. Some of the analyses, moreover, are old and obsolete, and evidently made without the precautions which are now recognized to be essential. Iron, for instance, is often all recorded as ferrous, no determination of the fact having been made. The figures for "water" often represent only loss on ignition, a method of estimation of notoriously fallacious character. In order to discuss the composition of glauconite the analyses must be carefully sifted and criticised, for much of the published material is entirely worthless.

"The recent series of glauconite analyses by Glinka,[a] made upon samples from various Russian localities, is of great value, for the reason that the glauconite grains were carefully separated from admixed impurities by

[a] Zeitschr. Kryst. u. Min., Vol. XXX, p. 390.

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means of Thoulet's solution, and the figures indicate that the work was done with care. The analyses are ten in number, and the five best, XXXV–XXXVIII, XLIV, in the table on page 241, made upon material dried at 100°, are as follows:

Analyses of glauconite.

Constituent.	XXXV.	XXXVI.	XXXVII.	XXXVIII.	XLIV.
SiO_2	48.95	49.75	49.53	51.00	52.96
Al_2O_3	7.66	7.82	5.84	9.93	12.76
Fe_2O_3	23.43	22.26	20.06	18.69	13.56
FeO	1.32	2.36	5.95	1.98	2.34
CaO	.57	.....	.56	.87	.....
MgO	2.97	3.25	2.92	3.85	4.11
K_2O	9.54	9.01	9.31	7.66	8.69
Na_2O	.98	.30	.46	.35	.47
H_2O	4.93	5.16	4.91	5.83	4.91
Total	100.35	99.91	99.54	100.16	99.80

"From these figures the following molecular ratios can be derived:

Constituent.	XXXV.	XXXVI.	XXXVII.	XXXVIII.	XLIV.
SiO_2	0.816	0.846	0.825	0.850	0.883
R_2O_3	.210	.216	.182	.214	.210
RO	.103	.114	.105	.138	.135
R_2O	.117	.101	.106	.087	.099
H_2O	.276	.287	.273	.324	.273

"Since RO and R_2O vary reciprocally, replacing each other, these factors may all be reduced to the general equivalent of R', giving the subjoined empirical formulæ:

XXXV.....$R'_{.440}R'''_{.420}Si_{.816}O_{2.040}$. 276 aq.
XXXVI.....$R'_{.426}R'''_{.426}Si_{.846}O_{2.115}$. 287 aq.
XXXVII.....$R'_{.541}R'''_{.364}Si_{.825}O_{1.967}$. 273 aq.
XXXVIII.....$R'_{.434}R'''_{.428}Si_{.850}O_{1.967}$. 324 aq.
XXXIX.....$R'_{.405}R'''_{.420}Si_{.883}O_{2.020}$. 273 aq.

"If we neglect the water as extraneous—that is, as 'zeolitic' or crystalline—and therefore not a part of the silicate molecule, these figures give quite closely the general formula

$$R'R'''Si_2O_6+aq.,$$

in which R' is mainly K, R''' is mainly Fe, and with the usual replacements

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of these radicals by others, as shown in the analyses. That is, glauconite, in its purest forms, must be regarded as a metasilicate, approximating more or less closely to the typical compound

$$KFe'''Si_2O_6+aq.,$$

which, however, like many other silicate molecules, has not yet been found in a state of purity. Such a compound would easily lose alkali and take up water, yielding, as Glinka observes, a ferruginous clay as its final product of alteration. Many of the observed variations in the composition of glauconite are due to partial alteration of this very obvious kind. The other variations represent the replacement of the iron salt by its aluminic equivalent and of the potassium salt by corresponding compounds of sodium, magnesium, and ferrous iron.

"In the case of the mineral described by Mr. Leith, to which he has given the name of 'greenalite,' the evidence is less complete. The substance is so intimately commingled with chert that it can not be isolated by ordinary physical means, and its composition, therefore, is only to be determined from that of the soluble portion of the mixture. This portion, according to the three latest analyses made by Mr. Steiger, representing the most carefully chosen material, has the composition given below.[a] The summation gives the total amount of mineral decomposed by hydrochloric acid in 100 per cent of the rock. Hygroscopic water is rejected.

Constituent.	4570.	4760.	4756.
SiO_2	13.45	19.30	33.11
Al_2O_3	.37	.61	.56
Fe_2O_3	15.00	13.83	6.44
FeO	10.28	17.57	30.93
MgO	2.33	3.22	5.35
CaO	.28	None.	None.
H_2O	4.17	5.74	6.13
CO_2	2.04	.....	.....
Total	47.92	60.27	82.52

[a] Professor Clarke's discussion was written without an opportunity to examine slides of the rocks analyzed, and hence no account is taken of the rock alterations. However, the alterations are slight and in no way invalidate Professor Clarke's main conclusion that the substance of the Mesabi green granules is different from glauconite. Indeed, were the alterations taken into account, and especially the alteration to ferric oxide, the basis for his conclusion would be strengthened. On pp. 108–115 the writer has discussed the analyses with reference to the alterations.—C. K. L.

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"To compare these data they must be reduced to corresponding terms. Accordingly, alumina has been recalculated into its equivalent of ferric iron, magnesia and lime into ferrous iron, and in the first example the carbon dioxide has been deducted, with its corresponding amount of monoxide bases. Then, recalculating to 100 per cent, we have the following figures to represent the composition of the soluble mineral:

Constituent.	45758.		45765.		45760.	
	Composition.	Ratio.	Composition.	Ratio.	Composition.	Ratio.
SiO_2	30.08	0.501	30.49	0.508	38.00	0.633
Fe_2O_3	34.85	.218	23.52	.147	8.40	.052
FeO	25.72	.357	36.92	.513	46.56	.648
H_2O	9.35	.519	9.07	.503	7.04	.391
Total	100.00		100.00		100.00	

"Although these ratios are not concordant, they still show something radically different from glauconite. If we restate them in the shape of empirical formulæ, we have—

No. 45758 ..... $Fe''_{.357}Fe'''_{.436}Si_{.501}O_{.2013}\cdot .519\ H_2O$
No. 45765 ..... $Fe''_{.513}Fe'''_{.294}Si_{.508}O_{1979}\cdot .503\ H_2O$
No. 45760 ..... $Fe''_{.648}Fe'''_{.10}Si_{.633}O_{.2370}\cdot .391\ H_2O$

"The first two of these expressions give quite sharply the orthosilicate ratio. The third represents a lower stage of oxidation, but something which is still far too high for a metasilicate. In the second case the composition approximates to the simple formula,

$$Fe'''_2Fe''_3(SiO_4)_3 .\ 3\ H_2O,$$

in which the ratios are those of a hydrated ferroso-ferric garnet. In the last of the three analyses the ferric oxide is very low and the ferrous oxide very high, which suggests the possibility that the original mineral may have been wholly ferrous, and that it has undergone partial oxidation in the other samples. The ratios $FeO:SiO_2$ is here 1:1, indicating a possible hydrated $FeSiO_3$ as the normal substance.

"The composition of greenalite, then, is uncertain. It may be a ferrous metasilicate, or it may be a ferroso-ferric orthosilicate. In either case the mineral differs fundamentally from glauconite, a potassium ferric metasili-

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cate, and can not be united with the latter species. Similarity, or even identity, of appearance under the microscope can not, in substances of this kind, offset the evidence of the ratios."

F. W. CLARKE.

Spurr's argument that the green granules of the Mesabi district are glauconite is based mainly on their similarity to glauconite in color and in shape, and on the fact that substances of a great variety of composition have been called glauconite by mineralogists, making it allowable for him to use the term for a somewhat exceptional phase in the Mesabi district. It is shown above that the green granules of the Mesabi differ from glauconite deposits in their association, in their thickness, and in several features of their composition. It is further shown that while no decisive proof of a definite chemical composition of the substance of the green granules in the Mesabi district has been brought forward, the facts are such as to indicate a distinct possibility that the green granules of the Mesabi have a definite and uniform chemical composition. While all these differences are thought to be more or less significant, the most significant difference between the green granules of the Mesabi district and glauconite granules is taken to be the entire absence of potash in the former. There seems to be the fullest authority for the statement that potash is an essential constituent of glauconite. If potash is an essential constituent of glauconite, then its absence is sufficient warrant for the conclusion that the substance of the green granules of the Mesabi district, whatever its origin, is not glauconite. As the substance corresponds to no other known mineral species and since a name is necessary to facilitate discussion of the substance, the name *greenalite* has been coined, as noted on a preceding page. If mineralogists and chemists, in view of the differences between the two substances above described, still think it desirable to stretch the term "glauconite" to cover the substance under discussion, it is suggested that the name "greenalite" may be retained as a varietal name under "glauconite."

EXPLANATION OF THE OCCURRENCE OF GREENALITE IN GRANULES.

The green granules of the iron-bearing rocks have been shown not to be glauconite, but to be a substance with a different composition which has been called greenalite; but the occurrence of greenalite in granules has

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not been explained. Are the granules normal concretions with radial and concentric structures about foreign nuclei, or are they concretionary or amorphous growths about, within, or replacing minute organisms, and thus directly analogous to glauconite?

1. None of the fresh green greenalite granules show any traces whatever of radial or concentric structure or of any foreign nucleus which is characteristic of concretionary or oolitic structures. Where altered in a few cases the iron oxide and chert or the different kinds of iron oxide have a rough concentric arrangement which may indicate that the original material possessed a concretionary structure, but which more probably has been developed secondarily and quite independent of the original structure of the granule. A few undoubted concretions consisting of concentric layers of iron oxide and chert about a nucleus of quartz are to be observed (Pl. XIII, fig. *D*). A concretion of this kind may be distinguished at a glance from the greenalite granules or their derivatives, even when the latter have rough concentric arrangement, as may be seen by comparison of the figures of Pl. XIII. These concretions are identical in shape with those described and figured by Van Hise as characteristic of the Penokee-Gogebic iron-bearing formation, in which they have developed from the alteration of iron carbonate.[a] (See Pl. XVI, fig. *A*.) There is carbonate associated with greenalite in the Mesabi district, and it is not impossible that the Mesabi concretions may have developed from carbonate, although no direct evidence of this has been observed. The true concretions of the Mesabi district also find their counterpart in concretions in the widely distributed Clinton iron ores, in which they probably developed at the time of the deposition of the ore. They are similar in form also, though not in substance, to the bavalite, chamosite, and berthierine of European ores.[b] Whatever the origin of the concretions in the Mesabi district, it is clear that they are quite independent of and subordinate to the greenalite granules, lacking evidence of radial or concentric structures or nuclei characteristic of true concretions.

2. The similarity of the granules of the Mesabi iron formation in general aspect to glauconite grains and to certain organic granules of the Clinton ores brings to mind very strongly the possibility that the shapes of the Mesabi granules may be determined by similar conditions. While

[a] Mon. U. S. Geol. Survey Vol. XIX, 1892. [b] See Lacroix, Minerals of France, p. 401.

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PLATE XXI.

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PLATE XXI.

PHOTOMICROGRAPHS OF GRANULES AND CONCRETIONARY STRUCTURES IN CLINTON IRON ORES.

FIG. *A*.—Granules in Clinton iron ore. From lower bed Sand Mountain, New England City, Ga. Loaned by C. H. Smyth, jr. Without analyzer, x 40. Granules of black and dark-brown hydrated hematite stand in a matrix of calcite. The latter areas within the granules are also calcite. Traces of organic shells in these slides are abundant. The granule a little to the right of the center shows this especially well. There can be no doubt as to the fact that the granules are for the most part replacements and accretions about shells and particles of shells. It is apparent also that there is a marked tendency for the granules to take on rounded and oval forms regardless of the shape of the original particles of shell. Note the remarkable similarity of these granules in shape to the greenalite granules illustrated in Pl. XIII.

FIG. *B*.—Green oolites in Clinton ore. From Clinton, N. Y. Loaned by C. H. Smyth, jr. With analyzer, x 40. Concentric layers of chloritic and siliceous substance, of various shades of green and yellow, surround angular, subangular, and rounded grains of quartz. The concentric greenish and yellowish bands under crossed nicols show black crosses characteristic of concretionary structures. The matrix is mainly calcite, but there are present also small particles of quartz.

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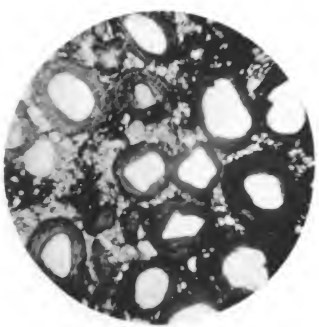
(A)



(B)

PHOTOMICROGRAPHS OF GRANULES AND CONCRETIONARY STRUCTURES IN CLINTON IRON ORES

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the greenalite is different in composition from glauconite, it might still be developed in much the same way. The close resemblance to glauconite grains in shape and physical properties other than specific gravity has already been noted. Noting the remarkable similarity in external shape between the Mesabi granules and granules of the Clinton ores of Wisconsin, the writer asked Dr. C. H. Smyth, jr., of Hamilton College, Clinton, N. Y., for slides of the Clinton ores, which occurr so widely in the eastern portion of the United States, and which he had described.[a]

Professor Smyth kindly furnished the slides requested, and thus enabled the following comparison to be made:[b] In the Clinton ores two kinds of granules are numerous: (a) Normal concretions of silica and iron oxide or of silica and some greenish substance with a ferrous iron base, the further composition of which is unknown, about a nucleus of quartz. (Fig. *B*, Pl. XXI.) These are analagous to the few true concretions observed in the Mesabi district and to the concretions of the Penokee-Gogebic district. (b) Accretions of iron oxide about calcium carbonate shells and partial or complete replacements of the shells, in either case without or nearly without radial or concentric structures. (Fig. *A*, Pl. XXI.) The size is somewhat greater than that of the Mesabi granules. It is noticeable that while traces of shells are abundant in the Clinton granules the shapes of the granules are not closely dependent upon the shape of the shell or fragment. On the contrary there seems to be a uniform tendency for the granules to develop with rounded and oval outlines no matter what the form of the shells which they replace. The shapes are almost identical with those of the normal greenalite granules of the Mesabi, as a comparison of Pls. IX, XIII, XV, and XXI will show. The similarity in shape is as close as between greenalite and glauconite. The crescent shapes, the gourd shapes, the much elongated ovals, and rods, which are seen associated with the round and oval forms in the Mesabi rocks are all to be seen in the Clinton ores The calcium carbonate of the shells in the interior of some of the granules of some of the Clinton ores also has a mottled appearance very similar to that observed in some of the Mesabi slides figured in Pl. XIV, although

[a] Am. Jour. Sci., 3d series, Vol. XLIII, 1892, pp. 487–496.

[b] In this connection a remarkable coincidence may be noted. In a letter of the same date Professor Smyth asked for information concerning the Mesabi granules. He had seen a brief preliminary description of them, by the writer, in Science, and had been struck with the similarity of certain of their features with those of the Clinton ores, with which he was familiar.

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beyond this there is no evidence that the two are the same. In both the Clinton ores and the Mesabi rocks a not uncommon feature is the accretion of a considerable number of granules into somewhat irregular pebble-like aggregates which have been waterworn as a whole and deposited parallel to the bedding. The Clinton granules differ from the unaltered Mesabi granules in that they are either iron oxide entirely or partly iron oxide and partly calcite, while the Mesabi granules consist of ferrous silicate when fresh and largely of iron oxide and chert when altered. The Clinton ores, in their present form, may not be concretions or replacements subsequent to their deposition, for they have uniform composition in thin beds over great areas, which could not be the case were they subsequently concentrated through underground water or other agencies. They may well be compared with the fresh greenalite granules of the Mesabi which also have undergone no concentration, rather than with the altered granules. If during the deposition of the Clinton ores the numerous minute shells had been surrounded and replaced by iron silicate instead of iron oxide, greenalite granules identical with those in the Mesabi district may have resulted.

It is concluded that the greenalite granules of the Mesabi district, while associated with a few typical concretions, are not for the most part normal concretions with radial or concentric structures about an inorganic nucleus; that from their remarkable similarity in shape to glauconite grains which are mainly developed as replacements, secretions, or accretions about minute organisms (although perhaps partly in other ways), and their similarity to the accretions about and replacements of shells in the Clinton ores, they may owe their shape mainly to similar development either within or about or replacing minute organisms of the variety commensurate with that now observed both in modern glauconite deposits and in the Clinton ores; that the development of greenalite instead of glauconite or iron oxide was largely a matter of substances present which were available for accretion, secretion, or replacement. However, the absolute absence of organic structures, aside from the suggestive similarity in shape to granules of known organic origin, must still be kept in mind, and the conclusion here given must be regarded as a tentative one, lacking sufficient basis of direct observation to render it final.

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MANNER OF DEPOSITION OF GREENALITE.

It now becomes necessary to determine how a compound like greenalite can develop under conditions such as those supposed to have existed in the Mesabi area. Two explanations suggest themselves.

1. DEVELOPMENT SIMILAR TO GLAUCONITE.

The material may have developed in a manner analogous to the development of glauconite. The manner of the development of glauconite is not by any means clear. Perhaps the most instructive work on the subject is that by Murray and Renard.[a] Quoting from their report concerning conditions for the development of glauconite:

> Where the detrital matters from rivers are exceedingly abundant and where there is apparently a rapid accumulation, glauconite, though present, is relatively rare; on the other hand, along high and bold coasts where no rivers enter the sea, and where accumulation is apparently less rapid, glauconite appears in its most typical form and greatest abundance. * * *
>
> * * * * * * *
>
> With reference to its bathymetrical distribution, it appears to be most abundant about the lower limits of wave, tidal, and current action, or, in other words, in the neighborhood of what we have termed the mud-line surrounding continental shores. In the shallower depths beyond this line, that is to say, in depths of about 200 and 300 fathoms, the typical glauconitic grains are more abundant than in deeper water, but glauconitic casts may be met with in deposits in depths of over 2,000 fathoms. No typical glauconitic sands have, so far as we know, been recorded in process of formation in the littoral or sub-littoral zones.[b]

Concerning its manner of development they state, tentatively:

> We are therefore inclined to regard glauconite as having its initial formation in the cavities of calcareous organisms, although we have admitted above that some grains which might be regarded as glauconite appear to be highly altered fragments of ancient rocks or coatings of this mineral on these rock fragments. It appears that the shells are broken by the swelling out or the growth of the glauconite, and that subsequently the isolated cast becomes the center upon which new additions of the same substance take place, the grain enlarging and becoming rounded in a more or less irregular manner, as in the case of concretionary substances like silica, for example, which forms molds of fossils. * * *
>
> * * * After the death of the organisms their shells are slowly filled with the fine mud in which they are deposited. The existence of this organic matter in these cavities, and the absence of all other causes which might there induce the deposition of the silicates, in fact, the constant association of these phenomena appear to demonstrate the existence of a relation of cause and effect. * * * If we admit that

[a] Report of the voyage of H. M. S. *Challenger*, 1873–1876, Deep-sea Deposits. [b] Loc. cit., pp. 382, 383.

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the organic matter inclosed in the shell, and in the mud itself, transforms the iron in the mud into sulphide, which may be oxidized into hydrate, sulphur being at the same time liberated, this sulphur would become oxidized into sulphuric acid, which would decompose the fine clay, setting free colloid silica, alumina being removed in solution; thus we have colloid silica and hydrated oxide of iron in a condition most suitable for their combination. To explain the presence of potash in this mineral we must remember that, as we have shown when speaking of the formation of pulagonite under the action of sea-water, there is always a tendency for potash to accumulate in the hydrated silicate formed in this way, and, as we have stated before, this potash must have been derived from the sea water.[a]

It is difficult to see how so high a percentage of iron as is found either in glauconite or in greenalite can be derived from the decomposition of mud filtered into the interior of the shell. If the mud were derived entirely from the disintegration of basic rocks, the percentage of metallic iron would not be far above 10 per cent, and the actual percentage found in the granules is far higher than this. The derivation of sufficient iron from the decomposition of mud would require a larger amount of foreign material than is contained in the casts. In the typical glauconite deposits foreign material is present outside of the shells, as shown by the above quotation from Murray and Renard concerning the constant accompaniments of glauconite, and there seems to be no reason why all of this material should not be drawn upon for the supply of iron. If the substance of the Mesabi green granules be supposed to have been derived from the decomposition of original detritus, this must have been present in enormous quantity, for the content of metallic iron shown in the analyses of greenalite rocks is 25 per cent, while the detritus available in the Mesabi area could scarcely have averaged as much as 7 per cent in metallic iron. As the greenalite rocks of the Mesabi iron formation accumulated to a thickness of perhaps 1,000 feet, it would be necessary to assume that a thickness of detritus several times this figure originally was present to yield the necessary amount of iron to the granules. There is ample evidence that no such amount of detritus (in fact little or none beyond that now to be observed) was ever present in the Mesabi iron formation. This consideration calls for an additional source for the metallic iron of the Mesabi greenalite granules; other possible sources are discussed under II and III below. The great thickness of the Mesabi iron-bearing formation as compared with known glauconite deposits is further presumptive evidence that processes other than those forming

[a] Loc. cit., pp. 388, 389.

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glauconite were active in the development of the Mesabi greenalite granules, for otherwise it would be necessary to assume abnormal intensity and duration of glauconite-forming processes.

While the explanation of Murray and Renard as it stands above scarcely seems applicable to the explanation of the origin of the Mesabi granules, it does not at all follow that the conditions and processes favorable to the development of glauconite when these are fully known will not be applicable, at least in part, to the development of the Mesabi greenalite granules.

II. DIRECT PRECIPITATION FROM SOLUTION BY ORGANISMS.

Where iron is being contributed to ocean waters in considerable abundance, it is possible to conceive of minute organisms abstracting the same and depositing it directly in some such form as glauconite or greenalite. This subject would require elaborate treatment and the explanation is here but mentioned.

III. DEVELOPMENT SIMILAR TO THAT OF IRON CARBONATE.

The association of the green granules in the Mesabi iron formation with original iron carbonates and their analogous composition suggest an explanation of their origin similar to that applied to the development of iron carbonates from other portions of the Lake Superior region by Irving and Van Hise.[a] This is outlined below.

IRON DERIVED FROM THE WEATHERING OF PREEXISTING ROCKS AND CARRIED TO THE OCEAN AS CARBONATE.

The iron and silica of the greenalite were brought into the ocean largely in solution. The rocks which at that time formed the shore (the Archean and Lower Huronian rocks) contained disseminated iron. The Archean "greenstone," which formed a very large proportion of the land area at that time, still contains from 7 to nearly 10 per cent of metallic iron, largely in the ferrous condition, and the Lower Huronian rocks less. By the ordinary processes of weathering the rocks were decomposed and the iron taken into solution by the surface waters, largely as carbonate. Most meteoric waters contain carbon dioxide (CO_2), and it is more than probable that sulphuric acid was also present, but was very subordinate in quantity to carbonic acid, and hence the sulphates were not important.

[a] See Mon. U. S. Geol. Survey Vols. XIX and XXVIII, and Twenty-first Ann. Rept. U. S. Geol. Survey, Pt. III.

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Particles of the preexisting rocks were also carried into the ocean in suspension, and these, by subsequent decomposition, yielded iron to the developing iron-formation materials, but it is not likely that this was a great factor in the development of the iron formation, for the average amount of metallic iron in such particles was less than 5 per cent, while the amount of metallic iron in the original iron-formation rocks is commonly 25 per cent.

THE IRON FIRST PRECIPITATED IN THE OCEAN AS A HYDRATED PEROXIDE.

When the waters bearing iron in solution reached the ocean most of the iron carbonate was broken up, the carbon dioxide given off, and the ferrous iron oxidized to a hydrated peroxide state and precipitated. The precipitate was probably first in the form of $Fe_2(OH)_6$, although the degree of hydration may have speedily altered, as it is known to do in the laboratory when it is allowed to stand or is subjected to various conditions. The reaction was

$$2FeCO_3+O+3H_2O=Fe_2(OH)_6+2CO_2.$$

Precipitation may have occurred either through the ordinary oxidation or with the aid of "iron bacteria."[a]

THE IRON FIRST PRECIPITATED IN AREAS OF VEGETATION.

It is probable that the ferric hydrate was thrown down in an area of abundant vegetation. Van Hise[b] has shown that the process of carbonation on a large scale, bringing the iron in form of carbonate to the ocean, is favored by the presence of abundant vegetation, the decomposition of which yields carbon dioxide; that where vegetation exists in land areas it is also likely to be abundant in adjacent waters where the conditions allow it; and that in such places carbonates are formed. The very fact that a formation high in iron content was deposited in the Mesabi area shows that some process was bringing in iron on a large scale, and no process would be more likely to be normal under the conditions under which the iron formation developed than carbonation. If the process of carbonation was occurring on a large scale this implies the presence both on land and in water of abundant vegetation. Moreover, the iron formation contains original carbon and carbonates of iron and calcium, affording direct proof of the presence of vegetation in the water in which the iron was first pre-

[a] For action of iron bacteria, see any standard text-book of bacteriology.
[b] Mon. U. S. Geol. Survey on Metamorphism, in preparation.

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cipitated. Still further, the iron formation, from its position between quartzite and slate, is known to have developed under conditions intermediate between those of clear water and muddy water, which would be likely to be favorable to vegetation. It has already been pointed out that instead of the open ocean, there may have been over this area a semi-inclosed arm of the sea. Such a condition would have been favorable to the extensive occurrence of this process.

THE HYDRATED PEROXIDE REDUCED BY VEGETABLE MATTER, AND THE PROTOXIDE OF IRON COMBINED WITH CARBON DIOXIDE OR SILICA.

As the hydrated peroxide fell to the ocean bottom and became mingled with vegetable material, and buried with it, it was reduced, at least in part. Says Van Hise,[a] "The reducing agent may be regarded as carbon monoxide, or some of the carburreted hydrogens, such as methane." The iron was then in the protoxide state and could easily combine with the carbon dioxide simultaneously developed by the oxidation of the carbon of the organic material to reproduce iron carbonate. But in addition to the carbon dioxide developed under these conditions silica was present. As shown by Van Hise, it is often frequently associated with carbonates, and it was associated with carbonates at the time of the development of the Biwabik iron formation, as shown by its present occurrence both in the altered and unaltered portions of the formation. The best investigation on the subject indicates that the chert is in most cases formed through the agency of pelagic organisms which secrete the silica found in solution in the sea water or derived from the decomposition of the silicate minerals in the associated detrital material.[b] The silica, especially where in a colloidal form, could combine with the ferrous iron present to form ferrous silicate. Thus in the development of the Biwabik formation both carbon dioxide and silica were present, with either of which the iron protoxide could combine according to the following simple reactions:

$$FeO+CO_2+nH_2O=FeCO_3+nH_2O$$
$$FeO+SiO_2+nH_2O=FeSiO_3nH_2O$$

The last-named formula essentially represents greenalite, though the subordinate constituents are not taken into account.

Whether the iron combined with the silica or with the carbon dioxide was probably a function of the relative masses of the chert and carbon dioxide

[a] Loc. cit.

[b] See C. D. Walcott, Mon. U. S. Geol. Survey Vol. XXX, 1898.

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available for combination. During the deposition of the Mesabi iron formation, silica was unquestionably in much greater mass than the carbon dioxide, as shown by the present composition of both the altered and unaltered portions of the formation. Doubtless there are other factors concerned in the combination of silica or carbon dioxide with iron, but these are not yet known. Whatever the cause, ferrous silicate was formed in great abundance and the iron carbonates in small quantity. Calcium and magnesium oxides, which may have been present, as shown by the analyses, may have reduced the active mass of the carbon dioxide available to unite with, and thus increased the proportional mass of silica. Both the magnesium and calcium oxides are stronger bases than the iron, and would take precedence over it on going into combination with carbonic acid.

In the iron formation of the Gogebic district of Michigan, a formation of the same age, general character, and associations, and supposedly of a similar origin, silica was less abundant in the original rock of the formation (siderite) than in the original rock of the Mesabi iron formation (greenalite rock), and thus the dominant combination was protoxide of iron and carbon dioxide, producing iron carbonate, and the combination of protoxide of iron with silica was very subordinate, although it did occur, as shown by the small admixture of ferrous silicate rocks in the carbonates of this region, already noted. (See p. 118.)

The preponderance of iron silicates in the Mesabi district and the preponderance of iron carbonates in the Penokee-Gogebic district suggests an analogy to the occurrence of zinc ores in Missouri and Wisconsin, described by Van Hise. In the former district zinc silicate is abundantly present with zinc carbonate. In the latter district zinc silicate is sparingly present with the zinc carbonate. Van Hise concludes that "the almost complete absence of zinc silicate in Wisconsin and the presence of zinc silicate in southwestern Missouri are in accordance with the well-known law of mass action. Where silica is abundant, so that zinc silicate can form, it is present plentifully; where silica is absent or subordinate, it does not develop in any considerable quantity."[a] In a later work he states: "Where, under the conditions described, silica is abundant in proper form,

[a] Preliminary report on the lead and zinc deposits of the Ozark region, by H. F. Bain, with an introduction by C. R. Van Hise; Twenty-second Ann. Rept. U. S. Geol. Survey, Part II, 1902, p. 51.

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the law of mass action requires its union with the protoxide of iron. This principle is illustrated by the condition in which the oxidized compounds of zinc occur in the Wisconsin and southwestern Missouri districts. In the Wisconsin district silica is not especially abundant, and where zinc sulphide is oxidized the zinc oxide unites with carbon dioxide and forms smithsonite ($ZnCO_3$) But in Missouri, silica, partly in the amorphous form, is very abundant; and there, when the zinc sulphide is oxidized, the oxide of zinc largely unites with the silica, forming calamine [$(ZnOH)_2SiO_3$]. Both smithsonite and calamine occur in both districts, but calamine occurs abundantly only where silica is abundant. Similarly, where in lagoons the iron is reduced to the protoxide form, it would unite with the silica on a large scale, provided that compound were abundantly present in a form suitable for union."[a]

CONCLUSION WITH REFERENCE TO ORIGIN OF GREENALITE GRANULES.

It is concluded that the explanation offered by Murray and Renard for the development of the modern glauconite deposits does not apply without much modification to the greenalite deposits under discussion; that the greenalite granules may possibly have developed directly from the abstraction, through the agency of organisms, of iron from solution in sea water, whence it was contributed from adjacent land areas; finally that a reasonable explanation seems to be that the green granules, from their analogy in composition to iron carbonate, from their association with iron carbonate, from their great thickness, their uniform character, and analogy with other carbonate and silicate compounds, probably developed in a way similar to the development of the iron-carbonate deposits of other portions of the Lake Superior region; and that their shape, and not composition, is determined by organisms. It may be noted in closing that the several explanations of the origin of the Mesabi green granules above outlined are not mutually exclusive, and each of them may be found to be partly true when the complete explanation is known.

[a] Mon. U. S. Geol. Survey on Metamorphism, in preparation.

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BURIAL OF THE IRON-BEARING FORMATION BENEATH THE VIRGINIA SLATE.

The iron-formation materials, consisting mainly of greenalite in the form of granules, abundant chert as cementing material and in layers, thin layers of iron carbonate, and layers of mud, were deeply buried under a great accumulation of mud, which, by its metamorphism, has given the Virginia slate formation. Judging from the present maximum thickness of the slate in the Penokee-Gogebic district, the depth of burial of the Biwabik formation beneath mud was thousands of feet and may have been as great as 13,000 feet.

EMERGENCE OF THE IRON-BEARING FORMATION FROM THE OCEAN.

The iron-bearing rocks came above sea level by the uplifting of the area. While the rocks were deeply buried under younger sediments long before the movement began, induration of the formation set in and continued during the uplift and, for parts of the formation, long afterwards.

ALTERATION OF THE IRON-BEARING FORMATION BY WEATHERING AND THE SECONDARY CONCENTRATION OF THE ORES.

As soon as the land appeared above the water, erosion began to wear down the rocks. The great thickness of slate had first to be removed, and it is probable that the iron formation was not exposed to weathering agencies until a very long period had elapsed. While part of the iron formation in the eastern end of the district was exposed by erosion before Keweenawan time, as shown by the fact that the Keweenawan gabbro there lies on the eroded edges of both the Virginia slate and the Biwabik formation, the central and western portions of the district in which the iron-ore deposits are now found were probably not exposed until post-Keweenawan time. Throughout the Lake Superior region the Upper Huronian and Keweenawan rocks were folded together, and there is reason to believe that this folding developed the Giants range and the southward tilting of the Upper Huronian strata over what is now known as the Mesabi district. This folding also fractured the brittle iron formation and made it very pervious to water. As soon as the folding had taken place erosion set in, which, after a long period, truncated the edges of the Upper Huronian series, giving them the distribution in belts parallel to the Giants range now to be observed.

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As the alteration of the iron formation and the concentration of the ore has been brought about by processes characteristic of surface conditions, as will be seen on a subsequent page, the secondary concentration of the Mesabi iron ores did not begin until after the truncation following the post-Keweenawan folding. The alteration which then occurred was as follows:

In its unaltered state the iron of the iron formation was disseminated through the rocks of the formation. The average amount of metallic iron was about 26 per cent. The alteration was rapid at the surface; but alteration was also carried on below the surface, both above and below the level of ground water, by the downward-percolating surface waters. The bedded structure, the attitude of the formation, and the cross jointing were favorable to the vigorous circulation of waters through the formation. Coming down the south slope of the Giants range they entered the truncated edges of the iron-bearing strata, dipping gently away from the range, and flowed southward along the layers. The chief alteration was that of the greenalite which, with the chert, made up the bulk of the formation.

The waters from the surface carried carbon dioxide and oxygen derived from the atmosphere and the carbon dioxide, perhaps in part from the erosion of the overlying slate and carbonates. They carried also small quantities of sulphuric acid and the alkalies. (See analysis on p. 264.) Hydrous silicates are readily soluble in underground waters, and especially waters bearing carbon dioxide. In the long period during which the ferrous silicate has been in contact with circulating waters bearing carbon dioxide it is apparent that it must have gone much into solution. The iron was thus brought into solution mainly as carbonate, though perhaps partly as sulphate or even as silicate. To illustrate the essential nature of the alteration of the greenalite, its composition will be assumed to correspond to the simple formula $FeSiO_3nH_2O$, thus neglecting the small amount of other substances shown by the analyses. The simple ratio of ferrous iron and silica shown in the formula has not been proved in the analyses, but what evidence there is points strongly to such a proportion. With this assumption the reaction was

$$FeSiO_3.H_2O + H_2CO_3 + Aq = FeCO_3 + H_4SiO_4 + Aq$$

The iron carbonate was either immediately oxidized and hydrated and thrown down as ferric hydrate through the agency of the oxygen carried

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by the solution which effected the carbonation, or the iron carbonate may have been in part carried a greater or less distance, until it met waters carrying abundant oxygen and was then thrown down. That transportation of iron in solution actually occurred is shown by the stalactitic and botryoidal ores in vuggs. Where ferrous compounds were abundant there was probably not oxygen enough to throw all of the ferrous compounds out of solution at once. The oxidation of the iron carbonate took place according to the following equation:

$$4\,FeCO_3 + 3\,H_2O + 2\,O = 2\,Fe_2O_3.3\,H_2O + 4\,CO_2$$

The degree of hydration may have varied at the time of the precipitation or thereafter through varying temperature or other causes.[a]

The solution of the iron silicate (greenalite) meant the simultaneous production of soluble colloidal silicic acid (see reaction, p. 261, and analysis, p 264), which carried the silica for greater or less distances and by dehydration deposited it as chert. The abstraction of the silica in this manner caused the iron oxides to slump and thus to be further concentrated.

This process, combined with the actual transportation of the iron in solution, where carried out on a large scale, resulted in the development of iron-ore deposits; where on a small scale the alteration resulted merely in the local segregation of the iron oxide and chert, giving ferruginous cherts.

The abstraction of the silica explains the slump near the contact of the iron-ore layers with the layers of wall rock described on pages 230–233. Indeed, one would expect the observed slump to be even greater than it is, for the silica taken out is over half of the volume of the original rock, as may be noted by comparing the analyses of the unaltered rocks and of the iron ores. But the ores after the concentration have a very large amount of pore space compared with the rocks from which they are derived, indicating that the iron ore has not fallen to an extent commensurate with the volume of the silica removed.

[a] The effect of temperature on the kind of hydrate precipitated is shown by the following analyses, by Hampe (Ch. Central-Blatt, 1889, II, 906):

	0°.	20°.	25°.	30°.	40°.	80°.	98°.	100°.
Fe_2O_3	54.6	51.4	50.4	46.1	43.9–53.2	66.2	70.1	72.3–92.7
Loss on ignition (H_2O)	45.4	48.6	49.6	53.9	.....	33.8	29.9	.....

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So far as the original iron-formation rock was an iron carbonate, which we know to have been present but to have been very subordinate in quantity to the greenalite, a similar set of changes occurred. The iron was oxidized and hydrated and the carbon dioxide removed in the manner described by Van Hise.[a]

At the same time the slaty layers within or adjacent to the iron formation which came into contact with actively circulating waters were altered to paint rock. The process consisted in the abstraction of substances other than the silica and alumina to a greater extent than these compounds, and staining red with iron oxide, due in part to the oxidation of the ferrous compounds contained in the slate and in part to introduction of ferric oxide.

Since the concentration was started in post-Keweenawan times the development of the ore bodies has had interruptions, but the interruptions probably have been subordinate as compared with the long periods during which the concentration has been occurring. In Cambrian times the district may have been covered by Cambrian sediments, but this is uncertain. The nearest Cambrian sediments are now 80 miles distant. Again, in Cretaceous times, the western part of the district, and perhaps the eastern part, were buried to an unknown depth by Cretaceous rocks, but when these were stripped off by erosion the concentration of the ores was resumed.

In Glacial times the Mesabi district was overridden by the ice and the surface rocks planed off. Large quantities of iron ore were removed at this time, as shown by the fact that fragments of ore are found in the drift, some of them of considerable size. The so-called Moose Track mine, south of the Fayal mine, was a large mass of iron ore of about 30,000 tons inclosed in the drift. Vastly more ore was carried away than now appears in large pieces in the drift, for the ore is of soft character and would be likely to be finely disseminated through the drift, or even carried away in solution. The glacial cutting of the ore is shown further by the fact that the rocks in the neighborhood of the iron-ore deposits, which are much harder than the ores, have been extensively cut down, as shown by the abundance of their débris in the drift; and as the surface of the ores is now usually below the harder wall rock, the softer ore was probably gouged out to a greater extent than the adjacent rocks. If in the past the upper portions of the deposits contained on an average a larger amount of hydrated ores than the lower

[a] Twenty-first Ann. Rept. U. S. Geol. Survey, Pt. III, pp. 326-328.

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portions, as they do now, then the glacial erosion removed more of the highly hydrated ore than of the less hydrated ore, and thus the present preponderance of hydrated ores in upper horizons is not so great as it might have been had glacial erosion not occurred.

In general, the glacial cutting has probably not been so deep as in the Canadian iron-bearing districts, or perhaps the Vermilion or Marquette districts, because of the protection of the high land to the north and also because of the interlobate position of the district, and this may help to explain the apparently greater abundance of ores in the Mesabi district than in the Canadian districts, as suggested by Van Hise.[a]

Since Glacial time the ore deposits have for the most part remained buried beneath glacial drift, but still the iron formation has been undergoing essentially surface alterations.

That the concentration of the ores is continuing at the present time is shown by the water analysis by Mr. E. T. Allen, of the United States Geological Survey, given below. The water is from a drift between the Hull and Rust mines west of Hibbing:

	Parts per million.
CO_3	71
SiO_3	22.35
SO_4	2.2
PO_4	Trace?
Fe	Not a trace.
Ca	10.1
K	.97

In all cases except in the determination of CO_3 1 liter was used. The water contained no suspended or precipitated matter.

The results are stated in terms of ions. Whether or not the ionization theory be accepted, the radicals given are the ones which have been actually determined in the analysis, whatever their state or combination.

The relatively high content of silica in the water indicates that this substance is now being taken out of the ore deposits and thus that concentration of the ore is actually occurring at the present time. The content of carbon dioxide, sulphuric acid, and the alkalies show the agents to be present now which presumably have been present in the past. The absence of any iron in the water is evidence that the concentration at the present time within the ore deposits already formed consists almost entirely, if not quite, in the abstraction of silica. It does not show, however, that in the past

[a] Twenty-first Ann. Rept. U. S. Geol. Survey, Pt. III, 1901, pp. 411–412.

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the iron itself may not have been carried in solution to form these ore deposits, nor that iron is not now being carried in those portions of the iron formation north of the Virginia slate and under the edge of the Virginia slate where greenalite or iron carbonate are available. At the present time ferrous silicate and ferrous carbonate are in exceedingly small quantity in the iron formation north of the Virginia slate, and their oxidation takes but little oxygen from the percolating waters which traverse the ore bodies. The waters, then, are likely to have a high percentage of oxygen throughout the part of the formation explored and the part from which the water analyzed was derived, and any ferrous compound which may get into solution is quickly oxidized and precipitated. In the past, when the ferrous compounds were abundant where the ore bodies now are, it may be supposed that the water was depleted in oxygen through the oxidation of the ferrous compounds before it had traveled any considerable distance into the formation, and that when the oxygen had been abstracted the ferrous compounds in solution may have been carried some distance before water bearing sufficient oxygen to oxidize and precipitate them was encountered.

LOCALIZATION OF ORES BY CIRCULATION OF WATER.

The segregation of the iron-ore bodies having occurred through the alteration of the greenalite by the agency of percolating underground waters, one would expect to find that the maximum alteration has occurred and the iron-ore bodies have developed at places where the circulation of the oxygen-bearing and carbonated waters was most vigorous. A consideration of the present and past circulation through the iron formation shows this to be the case.

Meteoric water falling on the iron formation, or contributed to it from the slope of the Giants range from the north, enters the eroded edges of the iron-formation beds dipping gently to the south Water probably flows along the bedding openings more freely than along the joints, for the bedding openings present more continuous openings than the joints, which are irregular and discontinuous, and are frequently cut off by soft, impervious layers which have yielded to deformation by bending rather than by breaking. Locally, however, the flowage along joints is dominant. Certain of the iron-formation layers also are porous, while others, particu-

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larly slate and paint rock, are not, and thus the water flows more easily through certain beds than through others. The flowage of water above the level of ground water and the flowage below this level have distinctive features and may be considered separately.

Above the level of ground water the water entering the iron formation tends to move vertically downward under the stress of gravity. If the substance were homogeneous this tendency would prevail and the movement would be practically vertical. Vertical joints in the iron formation tend to allow movement in this direction, but the more important bedding openings and the combination of pervious and impervious beds tend to make the water deviate from verticality and take up a course more nearly

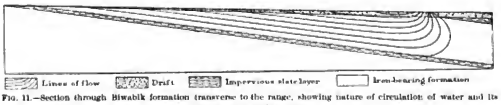

FIG. 11.—Section through Biwabik formation transverse to the range, showing nature of circulation of water and its relations to confining strata.

parallel to the beds. The major flow seems to follow broad gentle synclines in the iron-formation layers, but locally the flow follows cross fractures.

When the water has passed into the sea of ground water its flowage depends not only upon the structure and texture of the formation but upon the position of the outlet. It is certain that the water flowing through the Biwabik formation does not circulate vigorously far under the Virginia slate. Where the slate is drilled, in exploration, water is occasionally found under pressure, which shows that, in spite of the slight jointing of the slate, the formation is essentially impervious, as would be expected from any slate formation, and has ponded the water coming under it from the north. Thus water flowing through the iron formation must therefore necessarily overflow at the north edge of the slate Recent pumping operations have lowered the ground water to such an extent that in places it stands below the slate margin, and in these places there is little or no overflow at the edges of the slate. In the past, however, overflow at this level must have generally occurred. Slate layers within the iron formation and the Pokegama formation at its base must also limit the water circulations,

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several of which may have contemporaneously existed. Finally the circulation is modified by joints. The general nature of the flow of water parallel to the pitch of the formation between a slate layer within the iron formation and the overlying Virginia slate, or between any two slate layers within the iron formation, or between the Pokegama quartzite below and a slate layer within the iron formation, is shown in fig. 11, based on a drawing kindly furnished by Prof. C. S. Slichter. The lines of flow are drawn on the assumption that they enter the ground at equal distances along the upper slopes and emerge in a limited area in the drift near the margin of the slate. Probably more water enters the iron formation on the upper slopes than on the lower slopes, being contributed from the Giants range to the north. Were it not for this fact it would be necessary to leave wider spaces between the points of entrance of the lines of flow on the upper slopes than on the lower slopes. The diagram shows that the flow is more vigorous near the area of escape than elsewhere, just as, when water is drawn off the edge of a basin, the flow is more rapid at the point of escape than in a distant portion of the basin.

The actual flow through the iron formation differs from that shown in the diagram in a number of particulars. The iron formation between the impervious strata is not homogeneous, but the attitude of its layers and openings is such as to cause little vertical modification of the flow shown in the above diagram, for the beds and bedding openings would tend to carry the water in the same general direction. The effect of heterogeneity is only to make the vertical distribution more uneven than shown in the diagram. It must be supposed that while somewhat more water is coming to the surface near the edge of the slate than at any other horizon a considerable quantity of water is also coming to the surface in the iron formation a considerable distance away from this horizon, for the level of ground water is frequently in the drift above the rock surface. The total head, as shown by the configuration and attitude of the water table, varies from place to place and is seldom evenly distributed across the surface width of the iron-formation belt. An examination of the map will show much irregularity in topography, and numerous swamps and lakes, indicating ground-water level unevenly distributed through the formation. Perhaps in general the head is greater in upper portions of the belt, nearest the underlying rocks, than near the slate. Finally, in the past the water level and head have been changed from time to time, as will be seen below.

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Yet, notwithstanding these variations from the conditions represented in the diagram, it is thought that the diagram will serve as well as any other to show the general average conditions of flow below water level in the past before artificial openings had modified them. It is qualitatively, if not quantitatively, correct.

The lateral distribution of the flow depends upon the channels available and the level of the points of escape. Other conditions being equal, the flow is concentrated along joints or pervious portions of the formation. The water escapes at the lowest point, and hence near such a point the flowage is likely to be concentrated. Fracturing of the overlying Virginia slate or the slate layers within the iron formation may determine the lowest point of escape for a given area; or differential subaerial or glacial erosion may accomplish this result; or, finally, the original folding of the Upper Huronian series, followed by the truncation of the series by erosion, may result in making the low points of escape along synclines. It is probable in many cases that stream and ice erosion has followed the original structural synclines in the formation. In other cases it is certain that the anticlines have been cut off to as large or even a larger extent than the synclines.

While the flow is limited below by impervious strata, if, because of the position of the outlet, the flow below the level of ground water is greater near the point of escape than deeper down, it follows that there is no concentration of the flow along the impervious basement, and thus, in so far as the iron formation is below water level, there is no reason why water circulation should be more vigorous along the troughs than along the arches of the gentle folds, provided the openings in each case are equal and the points of escape at equal elevations. If, in the case of drawing off water from the edge of a basin, above cited, we assume the bottom of the basin to be gently flexed instead of flat, it is apparent that the circulation will be more vigorous near the top of the basin than below, and at the bottom there will be practically no difference in the circulation over the arches and the circulation over the troughs so far as both are below water level. Thus in the iron formation below the level of ground water, while the impervious layers limit the circulation below, their shape has no effect in concentrating the flow.

The distribution and shapes of the iron deposits and their relations to

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the adjacent rock strata are fully in accord with the idea that they have been localized by the circulation of water just described. The history of their localization, it is believed, was as follows:

When the formation was first exposed to surface alteration meteoric waters began to enter the formation. This was probably in early Cambrian time, long before the Glacial epoch, and the level of the ground water probably nowhere came to the rock surface. Indeed, there must have been over the exposed area of the iron formation a belt of weathering above the level of ground water, comparable in thickness with that now observed on the upper slopes of the Giants range where the drift covering is not thick. It is not uncommon to find here a belt of weathering as much as 100 feet thick, sufficient to include the greater bulk of the iron-ore deposits of the range at the present time.

In the belt of weathering the concentration of the ores, following the circulation of the water, was controlled in its major distribution by the broad, gentle folding of the formation, but locally was controlled by cross fractures. The ores were developed along irregular and ramifying fractures in the broad and gentle synclines, and not uncommonly several more or less independent deposits were developed in the same syncline. As noted on a prior page, under these circumstances the occurrence of the ores in synclines is frequently not directly shown by the attitude of the iron-formation layers immediately adjacent to the deposits, for the fractures along which the ores have developed may cross any part of the syncline and thus intersect layers with almost any attitude. Alteration once begun in any area, the abstraction of the silica made the rocks porous and tended to confine further circulation and consequent alteration to the same area. That the concentration of the ore deposits has occurred along cross fractures is shown not only by their distribution and shape, but by the fact that the contacts of the ore with the wall rock or with horses of rock within the deposit are plane surfaces intersecting at various angles, and when the ore has been removed the rocks stand out in castellated forms. The very existence of horses of rock in the ore deposit is evidence of the concentration along cross fractures which leave intermediate rock masses. Still further showing the control of circulation by fractures is the fact that many hand specimens may be collected showing plane surfaces with alteration extending a little way in from the surface, indicating the agent

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of the alteration—water—to have followed this surface. In general, the expression sometimes used locally on the range that the ore results from "rotting" along fractures may be close to the truth, although requiring certain modifications, as above indicated.

When the water passed below the level of ground water it continued its work of alteration, though perhaps not so vigorously because of its depletion in oxygen and carbon dioxide. But while the concentration was limited below by the slate layers of the iron formation, the concentration of the ores was not necessarily confined to openings in the broad synclines. In this part of its course the water concentrated ores along the largest and most continuous openings and near the lowest points of escape, regardless of the shape of the impervious basement. But in so far as the lowest point of escape was determined primarily by the folding, as it doubtless was to a great extent, the concentration occurred along synclines in the impervious

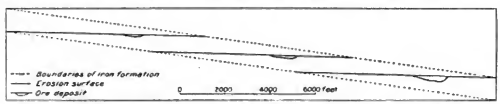

FIG. 12.—Sketch showing three stages in the downward and lateral migration of an ore deposit due to the truncation of the iron formation by erosion.

basement. This is illustrated by the Biwabik mine. The ore deposit is in general parallel to the strike of the iron-formation strata, but its thickest portion may be seen to lie near the lower point in the paint rock (the altered equivalent of the Virginia slate at this point) which may be seen to overlie the ore body. Also exploration to the south shows the slate to be cut back just opposite the "belly" of the deposit.

As the process of erosion continued the surface of the iron formation was cut down, and this was accompanied by a migration downward of the level of ground water, with the consequent emergence above this level of the part of the iron formation which had heretofore been below ground water. Any concentration which had occurred before this part of the formation came above water level was probably continued in the same areas, for such areas were rendered more porous by the alteration already undergone, but any new concentration was along the impervious basements of pitching troughs.

The erosion of the surface of the iron formation resulted in the lateral

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downward migration of the ore deposits. As the ore was cut off above, the development of new ore continued downward along the dip, its lowest limit always marked by an impervious stratum. Three hypothetical stages of the development of the ore deposit and its lateral migration are shown by fig. 12 (p. 270). It is apparent from this that the present state of affairs is merely a stage in a continuous process of concentration and migration, which is continuing to-day as it has in the past.

There is evidence that the area, before Glacial time, may have been near the sea level in two periods, the Cambrian and Cretaceous. At these periods the level of ground water must have been near the rock surface; the circulation was feeble and the concentration of the ore was slow and possibly ceased. At intermediate and subsequent times the level of ground water may be supposed to have been some distance beneath the surface. The circulation was then vigorous and the development going on.

In Glacial times a considerable portion of the upper part of the formation was scraped off. This included a large part of the formation which had been above the level of ground water, and thus many of the ore deposits and parts of ore deposits which had been concentrated in this belt. Associated with the glacial cutting was the deposition of a thick mantle of glacial drift, into which the ground water worked up. Since glacial time a large part of the iron formation has been below the level of ground water.

In summary, the localization of the ores through the circulation of underground water has been controlled primarily by the broad, shallow synclines[a] into which the iron-formation layers have been folded, but other factors have greatly modified this control and locally have been dominant. Of the modifying factors the principal one has been the cross fracturing of the iron formation, yielding openings through which the waters have flowed in devious paths and causing the concentration of the ores in limited and irregular areas within the synclines. Of scarcely less importance have been the little fractured and relatively impervious slate layers within the iron formation and the Virginia slate above the iron formation, limiting the circulation above and below, ponding the underground water, causing lateral

[a] Such synclines are not necessarily surface troughs, as sometimes assumed by explorers. They are evidenced by the attitudes of the layers of the iron formation, and may not be apparent in the unequally eroded rock surface or at the surface of the irregular covering of glacial drift.

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movements toward the lowest points of overflow, and finally causing the flow to be not necessarily confined to synclines but in some cases to be vigorous over anticlines, all combining to explain the concentration of iron-ore deposits with greater dimensions parallel to the strike of the iron-formation layers (parallel to the trend of the range), and deposits apparently independent of any synclinal structure in the iron formation.

EXPLANATION OF THE APPARENT ABSENCE OF ORE DEPOSITS AT THE EAST END OF THE RANGE.

Eastward from Mesaba station in the proximity of the Duluth gabbro the iron formation has no known ore deposits. The iron oxide present is mainly magnetite instead of hydrated hematite, and the associated minerals, aside from the chert, are characteristically monoclinic amphibole. These conditions indicate a history for this part of the district somewhat different from that above described for the part bearing the ore deposits.

The iron formation in the east end of the district was originally similar in character to that in the western and central portions of the district, though perhaps containing a little more intercalated slate. While the iron formation of the central and western portions of the district probably was not exposed to surface alteration until post-Keweenawan time, in the eastern end of the district the iron-formation rocks were exposed by the removal of the overlying slate before Keweenawan time. In Keweenawan time the eastern end of the district, and perhaps the central portion, were buried beneath Keweenawan rocks, principal among which was the Duluth gabbro mass of northeastern Minnesota.[a] In the east end of the district the gabbro came to rest on the eroded edges of the iron formation and slate. In the central and western ends of the district the gabbro was separated from the iron formation by a vast thickness of slate which up to that time had not

[a] If the iron formation had been exposed prior to the advent of the gabbro, and normal limonites or hematites formed to some extent, one might expect to find that the gabbro had metamorphosed these oxides into hard, brilliantly colored jaspers. This is apparently the explanation of certain of the jaspers in the Gogebic district. No such jaspers have been found in the Mesabi district, and their absence might be taken as evidence that the iron formation had not been exposed at the east end of the district prior to the intrusion of the gabbro. This evidence, however, it is believed will not stand against the evidence of the structural relations of the gabbro to the iron-formation rocks described on pp. 197–198. The lack of jaspers may rather indicate that the alteration under surface conditions prior to Keweenawan time had scarcely more than begun when the gabbro was intruded.

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been removed by erosion. The iron formation of the eastern end of the district, which had been exposed to surface weathering for a short time, was at the advent of the gabbro brought under deep-seated conditions of alteration. When thus buried and receiving heat from the cooling of the gabbro, the alterations were those of partial oxidation, perhaps deoxidation, dehydration, decarbonation, and silication, characteristic of such conditions.

The greenalite was altered without the presence of sufficient oxygen to bring the iron up to the ferric state, and the result was the development of magnetite, which may have gone through an intermediate hydrated stage. A temperature of only 19° C. is necessary to dehydrate the hydrate of the ferrous-ferric oxides. There is a possibility also that the magnetite may have been developed to some extent at this time by the dehydration and deoxidation of any small amount of ferric hydrate which may have existed at this time. Dehydration alone of the ferric hydrate may have also occurred.

A very characteristic change during Keweenawan time was the development of amphiboles. Grünerite, $FeSiO_3$, actinolite, cummingtonite, and perhaps other amphiboles, developed from greenalite by dehydration and the redistribution of the calcium, magnesium, iron, and silica in the granules and matrix. Where the original material was carbonate, as it was to a limited extent, the development of the amphiboles involved decarbonation and silication, the carbonate being carried away in solution.

Still another alteration characteristic of the Keweenawan was the marked recrystallization of the chert and the matrix, resulting in a great coarsening of the grain. (See pp. 159–160 and Pl. XVII.)

That the Keweenawan intrusion and burial were the main causes of the development of magnetite and the amphiboles is shown by the present distribution of these minerals, which are most abundant near the gabbro and decrease in amount as the distance from the gabbro increases, until in the central and western portions of the district they disappear almost entirely. Also near the gabbro contact the grain of the chert is the coarsest, and in leaving the gabbro the grain becomes finer.

Erosion subsequent to Keweenawan time uncovered a large portion of the iron formation of the district and brought the formation under conditions of surface alterations. The magnetitic, the amphibolitic, and coarsely crystalline rocks of the eastern portion of the district were very resistant to such

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alterations, in this differing from the iron-formation rocks of the central and western portions of the district, which, being soluble ferrous silicates, when first exposed to surface alterations were quickly altered. Thus the rocks at the east end of the range have remained practically as left by the gabbro. If there has been no further concentration of the iron in the eastern portion of the range since Keweenawan time, the amount of magnetite there to be observed measures the amount of concentration which had occurred in the formation when left by the gabbro. As already noted, magnetite has thus far not been found to be concentrated into workable deposits.

CAUSE OF THE DISTRIBUTION OF PHOSPHORUS.

Phosphorus, while locally very irregular in distribution, in general is more abundant in certain phases of the iron formation than in others. The paint rocks contain the highest percentage of phosphorus. These are followed in order by the yellow ores, the blue and brown ores, the ferruginous cherts, the unaltered slates, and the unaltered greenalite rocks. The last named contain little or none of this element. As the iron ores and the ferruginous cherts have resulted from the alteration of the greenalite rocks, and the paint rocks have resulted from the alteration of the slates, it is apparent that the alteration has been accompanied by the introduction of phosphorus; in other words, that the phosphorus in the ores and associated rocks has been mainly introduced from without and is not a residual product derived from the decomposition of the original rocks of the formation. Almost any of the rocks outside of the iron formation contain phosphorus, and some of them—for instance, the granite of the Giants range—contain more than is known in any of the rocks of the iron formation. Waters entering the iron formation, therefore, carry small quantities of phosphorus derived from the decomposition of such rocks. The amount may be small (the analysis of water on p. 264 shows but a trace); yet the amount of phosphorus in the ores and the adjacent rocks is usually a small fraction of 1 per cent, and when we consider the vast time during which the concentration has been occurring, it is apparent that but an exceedingly small amount of phosphorus need be in solution at any one time. The phosphorus is probably carried in solution as a phosphate.

The precipitation is believed to be occasioned by some aluminous compound. The paint rock, which has the highest content of phosphorus, has also a high content of alumina. Aluminum phosphate is insoluble, and

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this suggests the possibility that the aluminous mineral may be the precipitating agent. Some of the yellow ores also contain more alumina than the brown and blue ores (in part because of their content of paint rock), although it is doubtful whether any general statement that these ores contain high content of alumina can be made. So far as the yellow ores do contain more alumina than the blue or brown ores, their greater content of phosphorus would be in accord with the supposition that the alumina is the precipitating agent. Yet the phosphorus content is also high in yellow ores which probably do not have a higher alumina content than the brown or blue ores. For instance, in the Oliver mine, in 1899, a vein of limonite could be seen cutting down from the surface, clearly as the result of an alteration by percolating waters along a fissure, and the percentage of phosphorus within the vein was much higher than in the ore immediately adjacent. As alumina is very insoluble and not likely to be infiltrated along a fissure, it is not likely that the percentage of alumina in this vein is higher than in the adjacent ore.

It is not unlikely, also, that some of the phosphorus in the Mesabi ores occurs in the form of apatite. Prof. A. E Seaman, of the Michigan School of Mines, has found apatite crystals in the ores of the Michigan iron ranges, and it seems reasonable to suppose that they may also be found in the Mesabi ores, although the writer has thus far hunted for them without success. Even if the phosphorus is present partly or wholly as apatite, it is still believed that the constant association of phosphorus with alumina indicates that aluminous compounds are essential to the reactions precipitating the phosphorus compounds. It may be noted in this connection that in the Michigan iron ranges, where Professor Seaman has found the apatite, the close association of the phosphorus and alumina seems also to hold.

An interesting characteristic which the phosphorus compounds in the Mesabi ores possess in common with those in the Michigan ores is their solubility. When allowed to stand in the stock pile they are easily dissolved out. In the Biwabik mine ore shipped from the east stock pile was found to run .035 to .045 in phosphorus. When stock piled three years previous the phosphorus content varied from .050 to .065 and averaged about .060. Thus in three years the leaching out of phosphorus by ordinary meteoric agencies was sufficient to turn a distinctly non-Bessemer grade into a Bessemer grade.

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POINTS OF SIMILARITY AND DIFFERENCE BETWEEN MESABI ORES AND THOSE OF OTHER LAKE SUPERIOR RANGES.

The iron-ore deposits of the Mesabi are similar to those of the other Lake Superior ranges, commonly known as the "old ranges," in the following features:

1. They are concentrates from an original ferrous iron compound.

2. They have been concentrated by surface waters bearing carbon dioxide and oxygen.

3. They are located where the circulation of waters has been most vigorous.

4. They are mainly in pitching basins, at least in part bottomed by impervious strata.

The Mesabi iron-ore deposits differ from those of the old ranges in the following features:

1. The original material which by its alteration has given the iron ore in the Mesabi district, while a ferrous compound of iron, is mainly a silicate rather than a carbonate.

2. The pitching basins in the old ranges are formed by a folded impervious formation or by the intersection of the impervious formation with a dike, as in the Penokee-Gogebic district. The ore lies against the impervious wall rock at the bottom and also to a considerable extent at the sides. In the Mesabi district the ores, while largely confined to broad, gentle synclines, are in irregular bodies, occupying but a small part of the syncline, and the local attitude of the iron-formation layers immediately adjacent to the ores may give no indication of a synclinal structure.

3. The Mesabi ore deposits are for the most part shallow and have great horizontal dimensions, while those of the old ranges are deep and narrow. The Mesabi deposits are seldom deeper than 300 feet, and may have a considerably greater horizontal extent—in some cases more than a mile. Deposits of the old ranges may reach a depth of 2,000 feet or more, and seldom have a surface extent greater than a few hundred feet. On the Mesabi range the areal extent of the ore deposits is about 5 per cent of the entire iron formation, while in the old ranges the percentage is less.

4. The pitch of the deposits is uniformly less steep in the Mesabi range than in the old ranges. Average pitches range from 10° to 20°.

5. The Mesabi ores are much more hydrated than the ores of the old ranges, with the possible exception of those of the Gogebic range, and they are on an average of a softer character. The silica content also averages less.

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PREVIOUS EXPLANATIONS OF THE ORIGIN OF THE ORE AND THEIR RELATIONS TO THE EXPLANATION ABOVE GIVEN.

Explanations of the origin of the ore on the south shore of Lake Superior were early made by Hubbard, Rivot, Kimball, Hunt, Brooks, Wright, Houghton, and Locke, but it was not until 1869 that the carbonate theory now generally accepted was suggested. In that year Credner made the suggestion, with special reference to the Marquette district of Michigan, that the ores were derived from the alteration of iron carbonate[a]

In 1886 Irving[b] concluded that the iron-formation rocks, including the iron ores, of the entire Lake Superior region were derived from the alteration of an iron carbonate. This conclusion was based primarily on work in the Penokee-Gogebic district, but other iron-bearing districts, including the Gunflint area, had been examined for corroborative evidence.

In 1889[c] and 1892[d] Van Hise, who had done much of the field and petrographic work on which Irving based his conclusions as to the origin of the Penokee-Gogebic iron-formation rocks, presented detailed proof of the alteration of the Penokee-Gogebic iron-formation rocks from iron carbonate. In addition he showed the occurrence of the ores in pitching troughs with impervious basements where percolating waters are converged, and applied the long-accepted ideas of the manner of formation of iron carbonate to the iron carbonate in the Penokee-Gogebic district. Since 1892 Van Hise and his assistants have applied essentially the same explanation to the origin of the iron-bearing rocks and ores of the Marquette, Crystal Falls, Menominee, Vermilion, and in part to the Michipicoten districts,[e] the only exception being the Groveland formation of the Felch Mountain area, which Smyth[f] thought to have developed from the alteration of glauconite rocks, in this adopting Spurr's explanation of the origin of Mesabi ores noted below.

Little or nothing was known of the Mesabi hematite ores until 1891,

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[a] Die vorsilurischen Gebilde der "Oberen Halbinsel von Michigan" in Nord-Amerika, by H. Credner: Zeitschr. deutsch. geol. Gesell., Vol. XXI, 1869, p. 547.

[b] Origin of the ferruginous schists and iron ores of the Lake Superior region: Am. Jour. Sci., 3d series, Vol. XXXII, 1886, pp. 255–272.

[c] Am. Jour. Sci., 3d series, Vol. XXXVII, 1889, pp. 32–48.

[d] Mon. U. S. Geol. Survey Vol. XIX.

[e] Mon. U. S. Geol. Survey Vols. XXVIII, XXXVI, and XLV; Folio 62; Twenty-first Ann. Rept. Pt. III.

[f] Mon. U. S. Geol. Survey Vol. XXXVI, pp. 421–422.

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although the magnetites at the east end of the range had been known long before. In 1886 Irving[a] had stated that the Mesabi ores were developed from the alteration of iron carbonate, but this statement was based on scanty observations made to the east of the Mesabi range, at Gunflint Lake and vicinity. N. H. Winchell,[b] in 1891, concluded that the Mesabi ores were formed by chemical precipitation as hydrated sesquioxide in the Taconic ocean. In 1893 H. V. Winchell[c] first noted the occurrence of the Mesabi ores in pitching troughs, with the Pokegama quartzite as the impervious basement, where they were deposited by percolating waters flowing along natural underground drainage lines. The ores were supposed to result from the alteration of some one type of rock, for the most part not a carbonate, which he had not discovered, but from the associations and character of the formation thought probably to be a bedded oceanic chemical precipitate. Spurr[d] in 1894, by detailed microscopic work, determined the original rock of the iron formation to be made up of green granules in a matrix consisting essentially of chert. The green granules were found to be essentially ferrous silicate and to have many of the physical properties of glauconite. He concluded, therefore, that they are glauconite deposited through organic agencies in a sedimentary succession, and that the iron carbonates present in the iron formation are probably secondary to glauconite. The development of the iron ores from the green granules was emphasized. He followed H. V. Winchell in noting the concentration of the ore bodies by percolating waters upon the impervious Pokegama quartzite, and supposed the waters to have followed planes of weakness whether this happened to be along troughs or arches. Major faults of considerable displacement were supposed to account for the localization of many deposits. Spurr's explanation of the development of the Mesabi ores from glauconite rocks was accepted by N. H. Winchell[e] until 1900, when he announced that the green granules were volcanic sand.

Spurr's conclusion that the ores have developed from the alteration of green granules, consisting essentially of ferrous silicate, has been fully confirmed by the work done in preparation for this monograph; his conclusion that the green granules are glauconite grains has not been accepted;

[a] Loc. cit.
[b] Geol. Nat. Hist. Survey Minnesota, Bull. No. 6, 1891.
[c] Twentieth Ann. Rept. Geol. Nat. Hist. Survey Minnesota, 1893.
[d] Geol. Nat. Hist. Survey Minnesota, Bull. No. 10, 1894.
[e] Geol. Nat. Hist. Survey Minnesota, Final Rept., Vol. V, 1900, pp. 989-999.

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his conclusion that the iron carbonate is entirely secondary to glauconite has not been followed—some of it is secondary, but much of it also is unquestionably original and correlative in origin with the green granules; and, finally, his conclusion as to faulting in the area and the relation of faults to the localization of ores is not borne out by the present work.

In 1901 samples of the Mesabi green granules were submitted by the writer to the chemists of the United States Geological Survey and were found to have a composition indicating them not to be glauconite. On the basis of these results, Professor Van Hise, in his report on the iron ores of the Lake Superior region in the Twenty-first Annual Report of the United States Geological Survey (1901), pointed out the analogy in composition between the substance of the green granules and iron carbonate and their probably analogous development. Since the publication of this report, further analyses of the substance by chemists of the United States Geological Survey, discussed in the present monograph, have confirmed these results.

In the present report also attention has been paid to the cause of the occurrence of greenalite in granules and to the similarity not only to glauconite grains but to the organic deposits of the Clinton ores, and the conclusion is reached that the shapes of the granules may be essentially due to accretion, replacement, filling, or any combination of them, about organic bodies. Thus Spurr's conclusion that the granules owe their shapes to organisms is retained with modifications.

In the Twenty-first Annual Report cited, the development of the ore deposits by concentration through the agency of percolating waters was noted by Van Hise and the writer, and the circulation of the water was supposed to be controlled by the gentle cross folds in the iron formation, emphasized in the ore deposits by the slump due to the extraction of silica, by impervious slaty layers within the iron formation, by the overlying Virginia slate, and finally by planes of weakness formed by fracturing within the troughs.

In the present monograph emphasis is placed on the fact that, while the primary control of the circulation and consequent concentration has been exercised by the broad shallow synclines in the iron formation, other factors, such as fracturing, slate layers within the iron formation, and the overlying Virginia slate, have greatly modified this control and have been locally dominant.

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CHAPTER X.

MINING, TRANSPORTATION, PRODUCTION, RESERVE, OWNERSHIP, PRICES OF ORES, FURNACE USE OF ORES.

METHODS OF MINING.

A monograph on the Mesabi district would not be complete without brief reference to the interesting economic features connected with its mining industries. The writer is not competent to make a technically complete discussion of this subject, nor would it be advisable to give the necessary space to such a discussion in a monograph of this nature. It is the aim in the following chapter to present in nontechnical language a brief sketch of the more interesting and obvious economic features of the district which would be likely to interest the general reader and observer.

MINING BY STEAM SHOVELS IN OPEN CUTS.

Because of the soft character of the Mesabi ores and their occurrence in shallow deposits much of the ore may be loaded directly by steam shovels on railway cars in open cuts. This method may be observed (in 1902) in the Stevenson, Mahoning, Mountain Iron, Oliver, Sauntry-Alpena, Hale, Lectonia, Malta, Spartan (part), Fayal (part), Biwabik, and other mines. (See Pls. XXIV–XXVIII, XXX–XXXIII.) Several more mines will use this method in the immediate future. In 1902 about 47 per cent of the Mesabi ore was mined by steam shovel.

The procedure is simple. The glacial drift, or "overburden," or "surface," is stripped from the ore with steam shovels. The thickness of the drift removed may be only a few feet, or as much as 85 feet. The average is between 20 and 40 feet. Among mining men the expression is common that it pays to strip as great a thickness of drift as there is ore beneath. However, factors other than thickness of the ore beneath frequently determine the amount of drift that is advisable to attempt to remove. The total amount of drift which has had to be removed from

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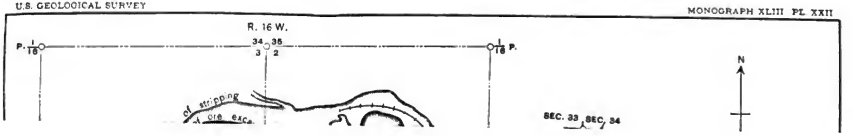

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some of the large deposits is very great, numbered by millions of cubic yards.

When the surface of the ore, or a part of it, is stripped, standard-gage railroad tracks are built out on the ore deposit and steam shovels make a cut through the ore. In this first cut the ore is either thrown to one side or is loaded on cars brought on a parallel track. After the first cut the shovel is set over against the bank and another slice is taken off and loaded on to cars run into the cut already made. When by a series of slices or cuts the bank or bench or level is carried back far enough, work is begun as before on a lower level, and in time this is followed by cuts on third and fourth levels, carving the deposit into a series of banks or terraces at several levels, against any or all of which steam shovels may work, giving access to a great variety of ores and making possible a large output in a short time. In the Mountain Iron mine the open pit has been made in this manner to rise in a series of terraces or levels from the central part of the deposit toward the edges. (See Pl. XXVI.) In the Mahoning mine the cuts have been first made in a spiral form, leaving a bank in the middle, so that subsequent cutting goes on both toward the center and toward the periphery of the deposit. (See Pl. XXXII.)

While the ore is soft it is usually too compact to handle economically without blasting, and so a small amount of this is done.

The systems of trackage vary from mine to mine. In the Mountain Iron mine the tracks enter the deposit at one place, slightly diverge, and run nearly parallel to one another on the different levels. (See fig. *A* of Pl. XXII.) The main track goes through the deposit and projects out the other end. The ore, however, is brought out where the tracks enter. As the ore layers dip in general in southerly directions, the tracks cross their strike and enable any desired grades of ore to be reached.

In the Mahoning mine the tracks enter at one place, but, instead of running straight through the deposit, they wind into the open pit in spiral curves, sending out tangential curves to the different levels. (See fig. *C* of Pl. XXII.) If in the Mahoning deposit the tracks had been put in according to the Mountain Iron system, the shape of the deposit would have required the tracks to be run parallel to the strike of the layers, thus making it difficult to get access to the variety of ores present. By laying the tracks in spiral curves this difficulty was avoided.

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In the Biwabik mine the tracks enter the mine at one point, make a gentle horseshoe bend in the deposit, and come out at another point. (See fig. B of Pl. XXII.) In 1901 one of the approaches was closed, and the tracks have since come into the deposit at one approach.

The Fayal system is illustrated on Pl. XXII, *D*.

MILLING.

This is a system adapted to the soft character of the Mesabi ores, but only a very small percentage of the Mesabi ores is mined in this way. The method is used (1902) in the Norman, Auburn, Adams (part), Jordan, Minorca (part), Morrow, Sharon, Fayal (part), and Duluth mines. About 7 per cent of the Mesabi production for 1902 was mined by this system.

The glacial drift is removed as in open-cut steam-shovel mining; a shaft is sunk in the adjacent wall rock to the level of the bottom of the deposit and drifts or cross cuts are run out through the ore; uprises, or chutes without timber, are sent up to the top from the cross cuts or drifts; by blasting the ore is then loosened at the surface, and pushed into the chutes by men with rods and shovels; it falls into cars stationed at the bottom of the chutes, is trammed to the shaft, and thence hoisted. Pl. XXX shows a view of the apertures of the chutes, known as the "mills," into which the ore is tumbled.

UNDERGROUND CAVING AND SLICING SYSTEMS.

Caving and slicing systems may be observed in the Penobscot, Burt, Sellers, Hull, Rust, Pillsbury, Clark, Union, Chisholm, Spruce, Commodore, Adams (part), Genoa, Sparta (part), Elba, Franklin, Kanawha, Roberts, Fayal (part), Agnew, Corsica, Croxton, Day, Fayal (part), Glenn, Grant, Hawkins, La Belle, Laura, Lincoln, Longyear, Minorca (part), Pearce, Pettit, Utica, Victoria, and Wills. About 46 per cent of the Mesabi production for 1902 was mined by these methods.

Shafts are sunk, usually in the ore close to the wall rock, and in some cases in the wall rock, well to the bottom of the deposit, although in places not to the bottom, because of the irregularities there likely to be encountered. Drifts or cross cuts are run out, either diagonally or in rectangular systems; timbered raises are sent up to the top of the deposit, and the ore drawn in from the top by drift slicing. The bottom of the drift

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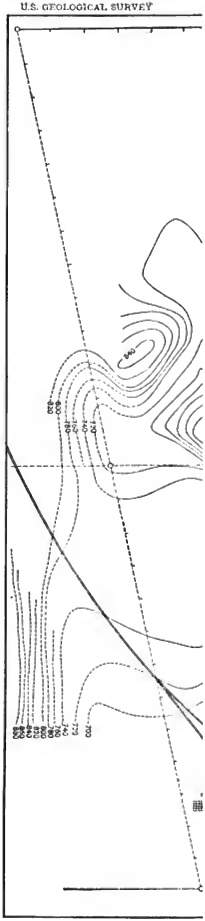

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is planked. As soon as one level or slice has been removed the surface or glacial drift is allowed to fall in or is blasted in, being kept from mixing with the ore by the planking at the bottom of the first level. Then another slice is taken out below on a sublevel, the planking and the surface allowed to fall in, as before, and so on, always working down.

In the rooming or square-set method, rooms, consisting of three or more sets from 20 to 40 feet wide, are run up from the main drift to the top of the deposit, the sides being lagged. Pillars of ore of about the same size as the rooms are left. The glacial drift is allowed to fall in from above, filling the rooms. The intervening pillars are then taken out by slicing either from the top or bottom.

Tramming is done mainly by hand or with mules, although of late electric haulage has begun to be introduced.

COMPARISON OF METHODS OF MINING.

A discussion of costs is out of place in a report the subject-matter of which is mainly geologic; but even from the above cursory description of mine methods it must be apparent that in general the open-pit method of mining is far the cheapest of the methods employed; that the underground methods are the most expensive; and that the milling methods are intermediate in cost.

The cheapness of the open-pit shovel method as compared with the underground mining is due to the large production possible, to the fact that timbering is not necessary, fewer men are required, lighting expense is less, all the ore can be moved (while in underground methods perhaps 10 per cent is lost), the ore can be better sorted, it has to be handled but once, tramming cost is saved, and the hoisting is by locomotive on a grade rather than through a shaft.

If open-pit steam-shovel mining is so much cheaper than the underground methods, the question is often asked why any of the Mesabi ores are mined by any other method. In order that a deposit may be worked satisfactorily with the open-pit steam-shovel method it must have considerable horizontal extent as compared with its length in order to afford proper grades to the tracks. The deposit must lie in a position to allow of an easy grade to the approach; this condition is met where a deposit is on a side slope. The thickness of the drift to be removed must

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not be too great, for otherwise the cost of stripping will run up the total cost of mining. There must be available ground with easy grades on which to deposit the dirt stripped off from the ore body. If there are capping layers of poor or unsalable ores these must be removed before the good ore can be mined. Or if it is desired to remove interstratified layers of good and poor ore independently it is not practicable by this method. Finally, the annual production must be large. Without a large annual production the interest on the preliminary investment for stripping, rolling stock, etc., necessary before a pound of ore can be moved runs the price of ore per ton up to a high figure. This preliminary investment is in most cases large.

On the other hand, when a deposit is opened up by an underground method there is little preliminary investment; no great mass of stripping has to be removed and disposed of; no layers of poor ore have to be removed before the good ore can be reached; the accessibility of all parts of the deposit does not depend on grade; the mine can be worked all the year round; and finally, the ore taken out while the mine is being opened goes to defray current expenses and to pay interest on the investment. Thus it is that while, where conditions allow it, open-cut mining costs less than half that of underground mining, in many cases it is still advisable to use underground methods.

The milling method is a combination of the open-cut and underground methods, and combines some of the advantages and disadvantages of both. It costs less than the underground methods of slicing and caving, because the timbering is less and all of the ore is saved, but it usually costs more than the open-cut steam-shovel method because of the shafts, drifts, uprises, and the tramming and hoisting.

The recent tendency has been greatly to increase the use of the open-pit steam-shovel method of mining. More of the new mines are opened in this way than formerly, and several of the mines which have in the past used underground methods will produce their ore by steam shovel in the future. There is also appearing a marked change in the policy of conserving ores. In the past it has often been the practice, because of market conditions or because of desire for immediate large profits, to take out high-grade ores finding ready sale wherever they were found, without regard to the grades that were left. The better, and for the most part the later,

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I RAILWAY CUT IN APPROACH TO OLIVER MINE, VIRGINIA.

Shows close jointing and brittle nature of the iron-bearing formation. The rock is a vitry phase of the ferruginous chert.

II PRELIMINARY STRIPPING AT OLIVER MINE, VIRGINIA.

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A

B

VIEWS OF OLIVER MINE, VIRGINIA, IN 1900.

A, Looking west. *B*, Looking east.

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practice has been to determine well in advance, in some cases even before any mining has been done, the grades of ore and their distribution for the entire deposit, and in the mining to make such selection and combination of these grades as to leave the lowest surplus of undesirable ores. The mining of the ore is planned to the end, as in building a structure, and is not influenced so largely as formerly by temporary conditions of market or management. The change is possible largely because of the new conditions of ownership whereby the control of the mines is in the hands of a few large steel interests.

TRANSPORTATION.

The Mesabi iron ores are transported to Lake Superior by rail, and thence by lake to terminal lake ports. The average rail haul is about 75 miles. Three railways carry the ore, the Duluth, Missabe and Northern, the Duluth and Iron Range, and the Eastern Railway of Minnesota.

The Duluth and Iron Range Railway carried the ore from the following mines shipping ore in 1902: Auburn, Fayal, Elba, Genoa, Sparta, Roberts, Hale, Malta, Kanawha, Spruce, Union, Franklin, Corsica, Minorca, Bessemer, Pettit, La Belle, Section 33, Victoria, and Wills.

The ore is delivered to Lake Superior docks at Two Harbors, Minn. The docks are five in number, with 776 pockets and storage capacity of 162,040 tons. The same railway also carries the ore for the Vermilion iron range, and the docks serve for both ranges.

The Duluth, Missabe and Northern Railway carried the ore from the following mines: Adams, Duluth, Pillsbury, Sellers, Burt, Oliver, Day, Hull, Rust, Biwabik, Mountain Iron, Glenn, Lincoln, and Spruce.

The ore is delivered to Lake Superior docks at West Duluth, Minn. These docks are three in number, with 960 pockets and storage capacity of 167,040 tons (Pl. XXXIII, *B*).

The Eastern Railway of Minnesota hauled ore from the following mines: Chisholm, Clark, Commodore, Mahoning, Penobscot, Saunitry, Stevenson, Alpena, Sharon, Grant, Pearce, Jordan, Longyear, Agnew, Morrow, Croxton, Utica, Laura, Hawkins, and Lectonia.

The ore is delivered to Lake Superior docks at Superior, Wis., two in number, with 500 pockets and a storage capacity of 103,000 tons. A third dock is in process of construction.

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The tonnage of ore from the Mesabi range carried by the three railways in 1902 is as follows:

Ore carried from Mesabi district by different railways.

	1902.
Duluth and Iron Range	3,538,978
Duluth, Missabe and Northern	5,610,407
Eastern Minnesota	4,180,568
Total	13,329,953

In density of traffic and freight earnings per mile of track there are but half a dozen roads in the United States which compare with these three railways, a fact brought out in the famous ore-rate case in which the State of Minnesota has made an unsuccessful attempt to have the rate on ore reduced. The rate from the Mesabi range to Lake Superior is uniformly 80 cents per ton.

The Duluth and Iron Range and the Duluth, Missabe and Northern railways and the docks at their termini are owned by the United States Steel Corporation. About 79 per cent of the ore which these roads hauled in 1902 was owned by the same corporation. The Eastern Railway of Minnesota, as already noted, is a part of the Great Northern system. None of the ore carried by this road was mined by the Great Northern, but by traffic contracts and fees it controlled 70 per cent of the ore it carried.

The ore has in the past been largely carried in wooden cars with a capacity of 25 to 35 tons. Within the last two years, however, steel cars of 50 tons capacity have been extensively introduced.

Revenue loads for single trains in 1902 averaged 1,400 to 1,730 long tons for the three railways, and the loads for double headers on the Duluth and Iron Range Railway averaged about 2,100 tons.

From Lake Superior docks the ore is carried in vessels to Lake Erie ports, or to Chicago and Milwaukee. The rate per ton has, since the opening of the Mesabi range, varied between 57 cents and $1.29½. The rate for 1902 was 75 cents.

The larger interests in the Mesabi district control their own lake steamers. The largest fleet, of course, is that of the United States Steel Corporation, which numbered 112 vessels in 1902, enabling this company to carry about 63 per cent of its own ore for that year.

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A

B

VIEWS OF MOUNTAIN IRON MINE

A. Looking north through mine. *B*. Steam shovel "tracking" bank of ore.

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A. SHARON MINE, SHOWING STRIPPING OPERATIONS.

B. AUBURN MINE OPEN PIT AND SHAFT.

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PRODUCTION.

The following table, taken (except for 1902) from the Iron Trade Review, shows the shipment, in gross tons, of iron ore in the Mesabi district since its opening in 1892:

Production in Mesabi district.

Name of mine.	1892.	1893.	1894.	1895.	1896.	1897.
Adams				59,141	234,582	170,738
Aetna (Lowmore)		1,645			17,723	
Auburn			108,210	376,970	131,478	175,283
Biwabik		151,500	90,048	247,069	242,565	427,464
Canton		24,416	213,853	359,020	16,261	
Cincinnati		26,372		17,187	57,324	32,912
Cloquet (Vega)			5,628	47,700	98,280	12,215
Commodore		65,137	7,213		22,063	60,708
Duluth		37,626				
Fayal				136,601	248,645	642,939
Franklin		46,617	223,399	286,423	231,086	30,128
Genoa					17,136	309,514
Hale		3,616	24,167	31,004	70,006	13,728
Lake Superior Group				58,123	67,650	259,912
Mahoning				117,884	167,245	519,892
Minnewas		13,858	2,140			
Mountain Iron (and Rath)	4,245	119,818	573,440	371,274	142,024	773,538
Norman			38,969	93,392	77,523	101,077
Ohio				28,943	69,925	47,350
Oliver (1)		123,015	505,955	500,377	808,291	601,072
Penobscot						11,933
Roberts						18,614
Sellers				47,433	153,037	
Sparta						66,722
Williams (North Cincinnati)				3,046	11,249	
Total	4,245	613,620	1,793,052	2,781,587	2,882,079	4,275,809

Name of mine.	1898.	1899.	1900.	1901.	1902.	Totals.
Adams	390,860	720,474	777,346	829,118	1,242,923	4,425,102
Aetna (Lowmore)						19,368
Agnew					45,582	45,582
Auburn	235,630	385,902	263,602	427,510	38,283	2,143,028
Biwabik	383,180	553,896	924,868	410,074	623,128	4,053,732
Canton		99,408				713,048

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Production in Mesabi district—Continued.

Name of mine.	1898.	1899.	1900.	1901.	1902.	Totals.
Chisholm	.....	.....	.....	34,573	200,629	235,202
Cincinnati	.....	246	.....	.....	.....	134,041
Clark	.....	.....	63,071	199,566	350,769	613,436
Cloquet (Vega)	.....	1,621	.....	.....	.....	163,444
Columbia	.....	.....	.....	15,627	.....	15,627
Commodore	80,494	152,947	278,416	35,546	65,833	708,447
Corsica	.....	.....	.....	26,838	59,294	86,132
Croxton	.....	.....	.....	.....	18,594	18,594
Day	18,651	1,975	.....	.....	106,516	127,142
Duluth	112,155	165,435	128,587	150,024	150,220	744,047
Elba	564	9,547	121,707	224,630	214,447	570,895
Fayal	575,933	1,072,257	1,252,504	1,656,973	1,919,173	7,505,025
Franklin	200,400	60,000	168,524	39,299	84,534	1,370,410
Genoa	279,677	276,559	253,651	332,022	399,719	1,868,278
Glenn	.....	.....	.....	.....	23,875	23,875
Grant	.....	.....	.....	.....	51,946	51,946
Hale	.....	18,807	32,901	30,929	54,289	278,447
Hawkins	.....	.....	.....	.....	5,892	5,892
Jordan	.....	.....	.....	.....	147,931	147,931
Kanawha	.....	14,963	64,218	41,300	24,830	145,311
La Belle	.....	.....	.....	.....	70,753	70,753
Lake Superior Group	135,404	154,326	284,023	504,761	766,312	2,320,520
Laura	.....	.....	.....	.....	3,575	3,575
Leetonia	.....	.....	.....	.....	28,785	28,785
Lincoln	.....	.....	.....	.....	87,779	87,779
Longyear	.....	.....	.....	.....	22,735	22,735
Mahoning	520,751	750,341	911,021	765,872	1,030,143	4,783,149
Malta	.....	28,615	65,346	126,260	192,874	413,134
Minnewas	.....	.....	.....	.....	.....	15,998
Minorca	.....	.....	.....	.....	35,500	35,500
Morrow	.....	.....	.....	.....	35,572	35,572
Mountain Iron (and Rath)	650,955	1,137,970	1,001,324	1,058,160	1,629,576	7,462,321
Norman	110,141	.....	.....	.....	.....	421,132
Ohio	101,607	293,651	172,597	.....	.....	714,673
Oliver (1)	349,100	.....	244,876	5,420	5,131	3,143,237
Pearce	.....	.....	.....	.....	54,885	54,885
Penobscot	29,652	85,619	146,641	221,080	209,431	704,356
Pettit	.....	.....	.....	.....	17,278	17,278
Pillsbury	99,691	106,487	101,032	120,723	238,122	666,055
Roberts	.....	57,847	41,965	42,756	28,972	190,154
Sauntry-Alpena	.....	53,004	68,560	328,739	249,837	700,140
Sec. 33	.....	.....	.....	.....	4,213	4,213

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Production in Mesabi district—Continued.

Name of mine.	1898.	1899.	1900.	1901.	1902.	Totals.
Sellers	112,765	174,807	56,280	34,918	193,428	772,728
Sharon				56,810	224,526	281,336
Sparta	226,156	237,143	202,144	156,426	252,674	1,141,265
Spruce			101,675	279,515	543,397	924,587
Stevenson			56,031	666,273	1,424,864	2,147,168
Union			8,297	93,109	103,521	204,927
Utica					9,009	9,009
Victoria					26,465	26,465
Williams (North Cincinnati)		12,357	18,298			44,890
Wills					12,159	12,159
Total	4,613,766	6,626,384	7,809,535	9,004,890	13,329,953	53,734,920

In 1891 the district had not been opened up. In 1895 the Mesabi district became the largest producer in the Lake Superior region, that year passing the Marquette district which, since 1854, had held first place. In 1901 the total production of the Mesabi district was 44 per cent of that of the Lake Superior region, and two and one-half times as much as its nearest competitor, the Menominee, which in 1901 for the first time surpassed the Marquette district in production. The combined production of four of the largest producers in the Mesabi district for 1901, the Mountain Iron, Fayal, Adams, and Mahoning mines, was greater than the total for the entire Menominee district for the same year. Beginning in 1899 the Fayal and Mountain Iron mines have shipped over a million tons each year, a record which has been made by no other mine in the world. The Fayal shipment in 1901 was 1,656,973 tons, an amount almost as great as the shipment for the entire Vermilion range for the same year. Largely on account of the Mesabi production the State of Minnesota in 1901 passed the State of Michigan as the largest iron producer in the United States. In total shipment the Mesabi district is still behind the Marquette district. At the close of 1901 the Mesabi district had shipped a total of 40,404,967 tons, while the Marquette district, open since 1854, had shipped 62,847,473 tons.

Comparing the Mesabi shipment for 1901 with that of the United States, it appears that the Mesabi district shipped 33 per cent of the total.

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In 1902 the Mesabi shipments showed an increase of 41 per cent over its own shipment for the preceding year and constituted 49 per cent of the total Lake Superior shipments for that year.

An examination of the general map of the Mesabi district (Pl. II) shows that there are many iron-ore deposits on the range which have not yet shipped ore. This is because of their grade or because of their late discovery or because they are controlled by companies which have enough ore for present shipments in properties already opened up. By leaving the ore untouched, taxes and the interest on the large investment necessary to open up a mine are saved. Other mines have been opened up and but small shipments made because more desirable ores or more cheaply mined ores were controlled by the same company in other mines. With the mines already opened up, including the steam-shovel mines, the annual production of the district could be enormously increased without opening any more deposits.

RESERVE TONNAGE.

The tonnage of individual properties ranges from a few thousand tons up to a possible maximum of 70,000,000 tons. Several deposits are known to have between 20,000,000 and 40,000,000 tons of ore. The total amount of ore of present marketable grade—that is, containing above, perhaps, 58 or 59 per cent of metallic iron—at present in sight on the Mesabi range has been estimated at 500,000,000 to 700,000,000 tons. Six hundred million tons is a commonly accepted figure. Of this, with proper mixing, perhaps 60 to 70 per cent is Bessemer ore. These figures are necessarily based on incomplete data, but they are commonly accepted by those best qualified to judge. Ore running below 58 or 59 per cent in metallic iron is known to be present in enormous quantity, but the amount has not been estimated nor are the data for an estimate likely to be available for some time to come. Within recent years steps have been taken to reserve the best of it. Ores running even as low as 50 per cent, while not exploited, are being put aside by the large companies for future use. At the mines where it has been found necessary to move low-grade ore in order to get at higher-grade ores, the low-grade ores are in some cases being stock piled where this can be done at a small cost.

The aggregate amount of high-grade ore in sight up to 1902 on all the "old ranges" of the Lake Superior region has been thought not greatly to

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exceed 350,000,000 tons. Even if the estimates for the Mesabi range and the old ranges are considerably away from the truth, it is certain that the Mesabi holds a commanding position in the region in its reserve tonnage. When it is remembered that even before the discovery of the Mesabi ores the Lake Superior region was regarded as the richest iron-ore-bearing region in the world, it is apparent that the Mesabi district has no peer.

OWNERSHIP AND CONTROL.

On the general map of the range are indicated the principal mining properties known up to the time the map was submitted to the printer. This information is based partly on a list and description of properties prepared by Mr. J. H. Gruber, land agent of the Eastern Railway of Minnesota, for property owners in the Mesabi district, to aid in the apportionment of taxes, but shows many subsequent additions and changes. The large amount of exploration and the rapidity with which discoveries of ore have followed one another make it certain that before the map comes from the printers iron-ore properties other than those indicated will be known. Moreover, properties are rapidly changing hands and the names of the mines are being changed, with the result that some of the names shown on the map will be superseded. The name of the mine or lease rather than the name of the owners is given whenever a name has been assigned. It has been the aim to include only such parcels of land as actually contained ore, but it has not been possible consistently to follow this procedure. It seems best in some cases to include the entire block of land covered by a well-known lease; for instance, the Kanawha mine is shown on the map to cover four forties, while only the southerly forties contain the ore.

For the sake of convenient reference by mining men, the sections have been divided into forties. Where quarter posts have been found, subdivision has been based on their location. Where not found, the sections have been proportionately divided. In this connection it may be noted that the subdivisions of the sections in the vicinity of Virginia and Eveleth and thence eastward to Mesaba station have been made by Mr. D. L. Fairchild for the Minnesota Iron Company and kindly furnished us for use on the accompanying map.

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To give a full and accurate list of the owners of the iron-ore properties would require an amount of labor which is scarcely warranted by the scope of this report. Moreover, the list would be out of date at a number of points before the books come from the printer, so rapidly are the newer properties changing hands. But in order to show the extent to which the control of the ore is concentrated into a few hands, the names of the companies or individuals controlling the shipments for 1902, and the mines operated by them, are given below:

United States Steel Corporation: Adams, Glenn, Auburn, Chisholm, Clark, Day, Duluth, Fayal, Genoa, Lake Superior group, Mountain Iron (and Rathbone), Oliver, Pillsbury, Sauntry-Alpena, Sellers, Spruce. In 1902 the United States Steel Corporation mined about 60 per cent of the total Mesabi production.

Republic Iron and Steel Company: Franklin, Union, Victoria, Pettit, Wills.

Pickands Mather Company: Elba, Corsica, Minorca, Utica, Malta (with St. Clair).

Interstate Mining Company (Jones & Laughlin): Lincoln, Grant.

Donora Mining Company (Union Steel Company): Penobscot, Sharon.

Joseph Sellwood: Hale, Kanawha, Croxton, Leetonia, Longyear, Morrow, Pearce.

G. A. St. Clair: Malta (with P. M. Co.), Sparta, Sec. 33.

Corrigan and McKinney: Stevenson, Commodore, Jordan.

Todd, Stambaugh and Co.: Mahoning.

Biwabik Mining Company: Biwabik.

Fay Exploration Company: Laura.

Drake, Bartwell and Co.: Roberts.

Deering Harvester Company: Agnew, Hawkins.

In most of the properties other parties are concerned, either in the fee or lease, but not directly in the operation of the mine.

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A. PANORAMIC V

B. PANORAMIC V

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EW OF ADAMS MINE.

EW OF FAVAL MINE.

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PRICE OF MESABI ORES IN COMPARISON WITH OLD RANGE ORES.

Below are listed the prices of Lake Superior ores at terminal lake ports from 1891 to 1901, quoted from figures given by A. I. Findley, editor of the Iron Trade Review:

Prices of Lake Superior ores.

Grade.	1891.	1892.	1893.	1894.
Mesabi Bessemer				$2.25 to $2.65
Mesabi non-Bessemer				1.85
Marquette specular No. 1 Bessemer				
Marquette specular No. 1 non-Bessemer	$5.00	$5.00	$4.00	2.90
Chapin	4.25	4.25	3.65	2.50
Soft hematites, No. 1 non-Bessemer	3.75	3.75	3.25	2.25
Gogebic, Marquette, and Menominee No. 1 Bessemer hematites	4.75	4.50	4.00	2.75
Minnesota No. 1 hard Bessemer	5.50	5.65	4.50	3.35
Vermilion No. 1 hard Bessemer				
Minnesota No. 1 hard non-Bessemer		4.85	4.00	3.00
Chandler No. 1 Bessemer		4.85	3.90	2.95
Marquette extra low-phosphorus Bessemer		6.00	4.65	3.50
Republic and Champion No. 1	5.50	5.50	4.50	3.25

Grade.	1895.	1896.	1897.	1898.
Mesabi Bessemer	$2.25 to $2.70	$3.25 to $3.75	$2.10 to $2.30	$2.15 to $2.25
Mesabi non-Bessemer	1.90	2.40	1.80 to 2.00	1.70 to 1.85
Marquette specular No. 1 Bessemer		4.50	2.80 to 3.10	3.10 to 3.35
Marquette specular No. 1 non-Bessemer	2.75	3.00	2.45	2.35 to 2.45
Chapin	2.55	3.65	2.40	2.56
Soft hematites, No. 1 non-Bessemer	2.25	2.60	2.25	2.20
Gogebic, Marquette, and Menominee No. 1 Bessemer hematites	2.90	4.00	2.65 to 2.85	2.75 to 2.95
Minnesota No. 1 hard Bessemer	3.40	4.55	3.11	3.36
Vermilion No. 1 hard Bessemer				
Minnesota No. 1 hard non-Bessemer	3.00	3.25	2.65	2.55
Chandler No. 1 Bessemer	3.05	4.25	2.92½	3.13
Marquette extra low-phosphorus Bessemer	3.55	4.90	3.42 to 3.46	3.65
Republic and Champion No. 1	3.30	4.50		

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Prices of Lake Superior ores—Continued.

Grade.	1899.	1900.	1901.
Mesabi Bessemer	$2.25 to $2.40	$4.40 to $4.90	$2.75 to $3.00
Mesabi non-Bessemer	1.90 to 2.10	4.00 to 4.25	2.35 to 2.65
Marquette specular No. 1 Bessemer	3.21 to 3.50	5.93 to 6.48	4.66 to 4.92
Marquette specular No. 1 non-Bessemer	2.50	5.00	3.65 to 3.85
Chapin	2.73½	4.96	3.78
Soft hematites, No. 1 non-Bessemer	2.00 to 2.15	4.15 to 4.25	2.85 to 3.15
Gogebic, Marquette, and Menominee No. 1 Bessemer hematites	2.80 to 3.25	5.50 to 5.75	4.25 to 4.65
Minnesota No. 1 hard Bessemer	.....	.....	.....
Vermilion No. 1 hard Bessemer	2.65	5.10	4.08
Minnesota No. 1 hard non-Bessemer	.....	.....	.....
Chandler No. 1 Bessemer	3.35	6.00	4.62
Marquette extra low-phosphorus Bessemer	3.85 to 3.90	6.80 to 6.90	5.65 to 5.75
Republic and Champion No. 1	.....	.....	.....

FURNACE USE OF MESABI ORES.

When Mesabi iron ores first came on the market it was not found practicable to use them to a greater extent than 33 per cent of the furnace charges, for the reason that, because of their soft character, they packed in the furnace. The term "flue dust" was commonly applied to them. Since that time the percentage used in the furnaces has steadily increased until in 1902 the average furnace mixture contained 49 per cent of Mesabi iron ore and 51 per cent of old range ores. In other words, they are mixed on an average in about the proportion of their production. Individual ores are used in proportions ranging from 35 to 100 per cent of the ore burden. It is not unreasonable to expect that, considering the relative abundance of the Mesabi and the old range ores available, the percentage of Mesabi ores used in furnace charges will slowly increase in the future as it has in the past. This change results in part from the present tendency to decrease the height of furnaces from the maximum sizes reached in late years, thus giving the ore less opportunity to pack.

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ADAMS MINE SHOWING HORSES OF ROCK IN OPEN PIT.

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A

B

VIEWS OF FAYAL MINE.

A Mills, *B*. Milling with steam shovel.

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A. SAUNTRY MINE, LOOKING NORTH.

The layers of ore in both banks can be seen dipping to the west. At the north end of the cut the ore has been cut back to the rock (ferruginous chert) and it there appears that the rock layers dip westward at the same angle. While the layers of ore and rock may be gently folded into a great synicline, pitching to the west, this fissure would be likely to be overlooked because of the great extent of the ore deposit along the strike of the monoclinally tilted strata.

B. FAYAL MINE, SHOWING STEAM SHOVEL "BUCKING" BANK OF ORE.

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CHAPTER XI.

EXPLORATION.

Exploration for iron ore in the Mesabi district is partly a matter of chance, as it must be in any ore-bearing district and especially in a district heavily covered with glacial drift. The iron ore thus far found in the Mesabi district, however, has been within certain limits.

Ore is confined to the Biwabik formation of the Upper Huronian series. The accompanying geologic map shows the distribution of the iron formation as indicated by the facts available up to the time of its publication. Where exploration has been insufficient, as in the western portion of the district, further work will show changes in the iron-formation boundaries. Examination of the drift may help to determine the boundaries in doubtful areas, for it is an observed fact that fragments of the iron formation have not been carried far in great abundance. The drift fragments have been carried in one direction, from northeast to southwest, and the discovery of fragments of iron-formation rocks indicates that the iron formation must be either beneath or to the northeast. Magnetic work may also be of assistance in locating the iron formation. In the productive portion of the district the iron formation is essentially nonmagnetic, yet over the area of the formation the magnetic attraction everywhere shows minor disturbance and this disturbance is particularly marked near the northern boundary of the iron formation.

The workable deposits thus far discovered are confined to the portion of the iron formation west of Mallman camp, in range 14. East of Mesaba station the oxide is largely magnetite and the associated rocks are actinolitic, grüneritic, slaty, and crystalline. Magnetite with such associates has not been found in workable deposits either in the Mesabi district or in the Penokee-Gogebic district, and if the explanation of the origin of magnetites given on preceding pages is correct, there is reason to believe that no large deposits of ore will be found in this area.

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The westernmost ore deposit thus far discovered is in R. 25 W. The ores near this western limit contain abundant particles of silica resulting from the disintegration of the chert associated with the ore, giving the ores what is known locally as a "sandy" character. Such ores can be used, however, by washing. The western limit of the area in which ores may be found in the future is as yet quite unknown. The map of the district accompanying this report covers an area extending only a little way west of Grand Rapids. It is certain that the iron formation extends well westward although deeply covered by glacial drift. Magnetic work and examination of glacial fragments has already shown the extension of the iron-bearing formation for several miles west of the limits of the map. Fig. 8, p. 203, shows the possible westward continuation of the belt and its connection with the Penokee-Gogebic series. If the concentration of the ore deposits is dependent upon vigorous circulation of the underground water, it may be suggested that the apparent flattening out of the Giants range toward the west may not give the waters of this area a sufficient head to circulate vigorously through the iron formation and concentrate the ores. The low-grade and sandy nature of the ores also may be in some way connected with this feature. However, it may be that the rock surface still has a considerable slope which has been covered and obscured by the drift, and if this is the case there is no apparent reason why ore should not be there developed. Certainly exploration for ore is warranted well to the west of Grand Rapids.

Unexplored land in the vicinity of known ore deposits is more likely to contain ore than is unexplored land in the vicinity of areas which have been explored and found barren, for in the former case it is certain that the conditions in the area as a whole are favorable to ore concentration, while in the latter they may or may not be. Applying this principle to the district in general, unexplored land in the central portion of the district is likely to yield larger returns in exploration than unexplored lands in the western and eastern ends of the district. While ore has been found in the western portion of the district it is not nearly so abundant as that found with an equivalent amount of exploration in the central portion of the district. It has been estimated that about 5 per cent of the area of the iron formation in the entire district is underlain by iron ore, while for the central area, between Mesaba station and the Hawkins mine, in R. 22 W., iron ore underlies more than 8 per cent of the surface.

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PANORAMIC VIEW

PANORAMIC VIEW

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MAHONING MINE

B

BIWABIK MINE

D

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The ore deposits have not been found in the portion of the iron formation which runs under the Virginia slate, nor are they likely to be found there, for the reasons that the circulation accomplishing the secondary concentration probably is not vigorous under the edge of the slate (see pp. 266–267); that the iron-formation rock there found has usually a fresh unaltered green character; and finally, while the slate has been pierced in a few places by drill holes, no ore has been found any distance under the true black slate, although the same number of holes similarly distributed almost anywhere else in the iron formation has scarcely failed to reveal ore. Attention is called to the fact, however, that the absence of ore under the black slate has not yet been demonstrated by actual drilling. Considering the magnitude of the new field opened further drilling seems warranted.

Being confined to the part of the iron formation not covered by the Virginia slate, the ore bodies for the most part lie between elevations 1,450 and 1,750 feet above sea level. Most of the iron formation north of the slate is between these elevations, so that this is simply another manner of stating that the iron ore is in the part of the iron formation not covered by the slate.

The iron ore is more abundant about midway between the north and south areal boundaries of the iron formation than elsewhere, as shown by the location of the existing deposits; yet many deposits are known to crowd both the north and south boundaries of the iron formation.

The ore deposits frequently underlie surface depressions. Their secondary concentration has been largely though not entirely along structural synclines; the leaching out of silica during concentration has caused a decided slump in the deposits; subaerial and glacial erosion has cut down the deposits perhaps to a larger extent than the surrounding harder rocks. The heavy and irregular mantle of drift deposited over the area by the glaciers has tended to obscure depressions, but in a large number of cases the underlying rock trough receives some expression in the overlying drift. Surface-drainage lines therefore are excellent areas to prospect. This does not mean that all surface-drainage lines mark the course of ore deposits, for the ores have not developed in all rock synclines, and, moreover, the depression in the glacial drift containing the surface drainage may be quite independent of the underlying rock topography. Neither is it true that every ore deposit occurs in a depression in the rock surface, for, as shown

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on pages 269–274, the ores in developing along planes of weakness below water level have not necessarily been confined to rock troughs, and often where so confined subsequent erosion may have cut down adjacent areas so irregularly as to leave the ore in higher areas than the surrounding rocks.

Northward swings of the northern margin of the iron formation or of the Pokegama quartzite may mark synclinal basins formed by the folding of the Upper Huronian series (though they may also mark areas in which erosion has not cut down so deep as in adjacent areas). As the ores commonly develop in synclines, the location of the synclines in this manner may be of assistance. As a matter of fact, however, the position of the northern margin of the iron formation is for the most part known after, and as a result of, exploration in the iron formation.

The ore deposits being localized by underground circulation and the underground circulation being limited by slaty layers, the location of such layers may give some information as to the direction in which the exploration should be carried. Because of the dip such slaty rocks may come to the rock surface. It is a fact that there is scarcely a large deposit in the district which does not show layers of paint rock, the altered equivalent of slate, below or above, dividing the deposit, or at any or all horizons. But in a given locality there is difficulty in determining whether the slate is really an interstratified layer in the iron formation, which may be associated with ore, or is the Virginia slate, which is probably not associated with ore.

In general the slates within the iron formation are perhaps more jointed and broken up into small parallelopiped blocks than is the Virginia slate; they have a predominance of red and brown tones, due to their large content of iron, as contrasted to gray and black tones in the Virginia slate; they are more siliceous and brittle; and they contain a lower percentage of alumina. Because discrimination by these criteria is so frequently doubtful, the position of the slate with reference to the supposed iron-formation boundary, or with reference to surrounding explorations showing iron formation or slate, is likely to be the guiding criterion in determining whether the slate belongs to the iron formation or to the Virginia slate.

The ore deposits have not yet been found to be covered by any considerable thickness of barren rock for any large proportion of their area, although shelves and irregular masses of rock project from the walls out

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A VIEW OF HALE MINE, SHOWING MONOCLINAL DIP OF STRATA OF ORE AND ROCK

The steeply dipping strata on the south are ferruginous chert. The longer dimensions of the ore deposit are parallel to the ferruginous chert wall. The deposit extends for a considerable distance to the west, its continuation is mined at the Kanawha shaft, to be seen in the distance. The layers of iron ore continuous with those of the wall rock to the south, although showing minor disturbances at the contact. It is apparent from this view that the ore is not in a pitching trough formed by the folding of the iron-formation layers, but is really in a long, narrow basin, upon the upper edges of monoclinal tilted strata.

B DULUTH, MISSABE AND NORTHERN ORE DOCKS AT DULUTH.

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over the deposit or into the deposit, or islands of rock may be surrounded above, below, and on the sides by ore. Wherever drills have reached ore in quantity after penetrating any considerable thickness of rock it has been found that the ore appears at the surface a short distance away. Up to the present time there has not been enough deep exploration in rock to prove the nonexistence of ore in bodies entirely covered by rock and nowhere reaching to the surface. In view of the fact that all ore thus far known is only very locally and very partially covered by rock, shallow exploration over wide areas is likely to show the greatest percentage of finds, but deep drilling is also warranted. In the future many areas in which there has been shallow exploration will need to be explored deeply to prove whether or not ore actually occurs beneath them.

The ore deposits are associated with characteristic altered varieties of the iron formation which are familiar to all who have worked long with the ores. Nearly every mining man or explorer has in mind certain phases of the ferruginous chert which he is accustomed to associate with ore deposits. Pls. X and XI show several of the phases frequently associated with ore On the other hand, other phases of the iron formation are seldom found in association with ore, and thus are avoided in exploration. Figs. *A* and *B*, Pls. VIII and XII, represent certain of these phases. Further discriminations are made by Mesabi explorers, but they are not described because of doubt as to their general application.

The question has been asked, "What are the chances of finding ore in the Lower Huronian and Archean rocks?" Iron ore is known in both series in other districts of the Lake Superior region, and there is no a priori reason why ore should not be found in either or both in the Mesabi district. However, both series are fairly well exposed, have been thoroughly examined, and not only has no iron ore been found, beyond a few ferruginous discolorations in the hornblende-schists, but no iron-formation rocks have been discovered. Stray fragments in the conglomerate at the base of the Upper Huronian show that iron-formation rocks were present in the Lower Huronian and Archean areas from which the fragments of the conglomerate were derived, but they may have come from a considerable distance outside the Mesabi district, perhaps from the Vermilion.

Exploration should be governed by the above conditions so far as they are known, but it is never possible to know all of these conditions in

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advance of exploration. When the district was first explored none of them were known. To-day but a part of them are available for locating exploration, but all of them may be of assistance in interpreting the facts brought to light after exploration has once begun. As a matter of practice but little exploration has been done in which all these criteria have been taken advantage of, particularly the criteria developed from the flowage of ground water. In most of the cases a part of them have been used, but they have been subordinate to other conditions—the lands available for exploration at the time, favorable terms, etc. The unit of land transfers is one-sixteenth of a section, or 40 acres, and it has been a very common practice to put the holes down systematically over the "forty" regardless of any criteria for closer location of the ore which might have been present.

Exploration is done in the Mesabi district by test pitting with pick and shovel, by churn drilling, and by diamond drilling. In the early days the work was done almost entirely by test pitting. In later years drilling has come commonly into use. In the year 1902, 200 drills, diamond drills and churn drills, were continuously in use in the Mesabi district. A hole is put down entirely by drilling or by test pitting until water or rock is struck and then by drilling below. Because of the fairly soft character of the formations churn drilling, in which the cutting is done by percussion, is more common than diamond drilling, in which the cutting is done by rotation of a steel bit with diamonds set in its periphery. The cost of test pitting since the opening of the range has varied from $1.25 to $3 per foot; $1.25 is the present price. The cost of drilling has ranged from $2 to $3.50 per foot for ore and from $4 to $7 for rock, depending upon the nature of the ore or rock. The higher prices are the later ones.

E. J. Longyear has called attention to errors in determining the true composition of an ore by drilling. The choppings of the drill are brought to the surface by water forced through casing pipes, are allowed to settle, are dried, and then analyzed. If the ore is not allowed to settle for a considerable length of time the lighter materials associated with the ore are likely to be retained in suspension, and the analyses of the ore therefore show a higher percentage of ore and phosphorus than they ought to. A mixture of blue ore, brown ore, yellow ore, and paint rock was analyzed, and found to contain 59.23 per cent of iron and .087 per cent of phosphorus. When treated with water and allowed to settle for twenty minutes, dried,

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and analyzed, the content of iron was 60.80 per cent and the content of phosphorus .094 per cent. When allowed to settle for sixteen hours, dried, and analyzed, the content of iron was found to be 59.67 per cent and that of phosphorus .088 per cent.[a]

In no other district of the Lake Superior region, or for that matter of any other region, have the rewards for exploration been so great as in the Mesabi. Since the opening of the range practically every explorer who has gone at the work systematically and on a large enough scale has succeeded in finding ore.

[a] Trans. Am. Inst. Min. Eng., Vol. XXVII, 1898, p. 540.

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